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ATTORNEYS FOR PLAINTIFF
OPTOPLEX CORPORATION

ORIGINAL

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NOV 26 2012
RICHARD W. WIEKING
CLERK, U.S. DISTRICT COURT
NORTHERN DISTRICT OF CALIFORNIA
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UNITED STATES DISTRICT COURT

NORTHERN DISTRICT OF CALIFORNIA

OPTOPLEX CORPORATION Plaintiff, vs. O-NET COMMUNICATIONS (USA), INC., O-NET COMMUNICATIONS GROUP LTD. Defendants.	CV 12- 5996 KAW CIVIL CASE NO.: COMPLAINT FOR PATENT INFRINGEMENT DEMAND FOR JURY TRIAL

WHITE & CASE LLP
ATTORNEYS AT LAW

FAXED

Plaintiff Optoplex Corporation ("Optoplex" or "Plaintiff") files this Complaint for patent infringement against Defendants O-Net Communications Group Ltd. and O-Net Communications (USA), Inc. (collectively "O-Net" or "Defendants"). Plaintiff alleges as follows:

THE PARTIES

1. Plaintiff Optoplex is a corporation duly organized and existing under the laws of the State of California with its principal place of business at 3342 Gateway Blvd., Fremont, CA 94538 in this district.

2. On information and belief, Defendant O-Net Communications Group Ltd. is a corporation organized and existing under the laws of the Cayman Islands and having its principal place of business at #10-1 S, Maqueling Industrial Park, Nanshan District, Shenzhen 518057, China.

3. On information and belief, Defendant O-Net Communications (USA), Inc. is a corporation organized and existing under the laws of the State of California and having its principal place of business at 756 San Aleso Ave., Sunnyvale, CA 94085 in this district. On information and belief, O-Net Communications (USA), Inc. is a subsidiary of O-Net Communications Group Ltd.

4. On information and belief, Defendants O-Net Communications Group Ltd. and O-Net Communications (USA), Inc. sell optical interleavers, differential phase-shift keying ("DPSK") demodulators, and/or other products with similar features or functionality ("O-Net Devices"), which are used in various telecommunication products such as fiber-optic communication. On information and belief, O-Net Devices or products containing O-Net Devices are sold in this judicial district, in California, and elsewhere in the United States through various means, including through a sales representative company Multiwave Digital Solutions, Inc., which has a place of business at 44790 S. Grimmer Blvd., Suite #201 Fremont, CA 94538.

NATURE OF THE ACTION

5. At issue is a patent infringement action brought by Optoplex against O-Net for infringement of United States Patent Nos. 6,587,204 (the "'204 patent") and 7,522,343 (the "'343 Patent") (all collectively, "Optoplex's Patents").

6. On information and belief, O-Net has infringed, and continues to infringe Optoplex's Patents by, among other things, making, importing, using, offering to sell and/or selling O-Net Devices and/or other similar products that practice one or more claims of Optoplex Patents in the United States and in this judicial district.

7. On information and belief, O-Net has infringed, and continues to infringe, Optoplex's Patents by contributing to the infringement of, and/or actively inducing others to infringe the claims through the sale of O-Net Devices and/or other similar products that practice one or more claims of Optoplex's Patents to its customers in the United States and in this judicial district.

JURISDICTION AND VENUE

8. This action arises under the patent laws of the United States, 35 U.S.C. § 1 *et seq.*, including 35 U.S.C § 271. This Court has subject matter jurisdiction pursuant to 28 U.S.C. §§ 1331 and 1338(a).

9. This Court has personal jurisdiction over O-Net because O-Net has substantial contacts and conducts business in the State of California and in this judicial district, and has been infringing, contributing to the infringement of and/or actively inducing others to infringe claims of Optoplex's Patents in California and elsewhere in the United States.

10. Venue is proper in this Court pursuant to 28 U.S.C. §§ 1391(b), 1391(c), 1391(d) and/or 1400(b) because a substantial part of the events giving rise to the claims at issue occurred in this District.

11. This Court has personal jurisdiction over O-Net by virtue of the businesses activities they conduct within this District and within the State of California, resulting in sufficient minimum contacts with this forum.

FACTS

A. Optoplex

12. Optoplex is a trusted provider of various innovative telecom components, modules and subsystems for communications networks. Optoplex focuses on designs, developments, and manufacturing of a broad platform of cutting-edge customized fiber-optic products for the

telecom network systems, which allow network systems to more effectively utilize their current resources.

13. Since June 2000, Optoplex has made large-scale investments in research and development activities by assembling a seasoned team of optical design, packaging and thin-film coating experts to revolutionize the fiber-optic products, thereby paving the path to the next generation of communication systems.

14. Optoplex has spent millions of dollars on research and development of its valuable technologies. Optoplex relies on the United States patent system to protect the technologies resulting from its research and development. Optoplex currently owns more than 20 United States patents and has many pending patent applications.

B. <u>Asserted Patents</u>

15. Plaintiff Optoplex is the sole owner by assignment of United States Patent No. 6,587,204, which issued on July 1, 2003, and is entitled "Application of a Step-Phase Interferometer in Optical Communication." A copy of the '204 patent is attached hereto as Exhibit A.

16. Plaintiff Optoplex is the sole owner by assignment of United States Patent No. 7,522,343, which issued on April 21, 2009, and is entitled "Michelson Interferometer Based Delay Line Interferometers." A copy of the '343 patent is attached hereto as Exhibit B.

FIRST COUNT
O-NET'S INFRINGEMENT OF U.S. PATENT NO. 6,587,204

17. Optoplex incorporates by reference paragraphs 1 through 16 above as though fully restated herein.

18. Optoplex is the sole owner by assignment of the '204 patent and possesses all rights of recovery under the '204 patent, including the right to sue for infringement and recover past damages.

19. Upon information and belief, O-Net has infringed and if not enjoined, will continue to infringe one or more claims of the '204 patent by performing, without authority, one or more of the following acts: (1) making, using, importing, offering for sale, or selling in the

United States O-Net Devices that infringe one or more claims of the '204 patent, in violation of 35 U.S.C. §271(a); (2) inducing infringement of one or more claims of the '204 patent in violation of 35 U.S.C. §271(b); and/or (3) contributing to the infringement of one or more claims of the '204 patent in violation of 35 U.S.C. §271(c).

20. O-Net's acts of infringement of the '204 patent, literal and/or under the doctrine of equivalents, include making, using, offering to sell, or selling, in this District or elsewhere in the United States, O-Net Devices and/or other similar products that practice one or more claims of the '204 patent, including 50G/100G Optical Interleaver.

21. Upon information and belief, O-Net has induced and continues to induce infringement of one or more claims of the '204 patent in this District and elsewhere in the United States, by, among other things, actively encouraging, or otherwise causing its customers to use O-Net Devices and/or other similar products that practice one or more claims of the '204 patent, such as 50G/100G Optical Interleaver.

22. Upon information and belief, O-Net has had knowledge of the '204 patent prior to the filing or upon service of the Complaint in this action, and continues to encourage, or otherwise cause its customers to use O-Net Devices and/or other similar products in a manner which infringes one or more claims of the '204 patent.

23. Upon information and belief, O-Net has specifically intended that its customers to use the accused products in such a way that infringes the '204 patent by, at minimum, providing datasheets, white papers, manuals, and/or technical support to its customers on how to use the accused products in such a way that infringes the '204 patent.

24. Upon information and belief, O-Net has contributed to and continues to contribute to the infringement of one or more claims of the '204 patent by offering to sell, and selling to its customers, in this district and elsewhere in the United States, the accused products that constitute a material component of a device, system, combination or composition covered by the '204 patent, and that the customers have utilized said products in a manner that infringes one or more claims of the '204 patent.

25. Upon information and belief, O-Net has been aware, since at least the service of

this action, that its products accused of infringement including, but not limited to, the accused products are especially made and/or adapted for use(s) that infringe one or more claims of the '204 patent and are, therefore not staple articles or commodities of commerce suitable for substantial non-infringing use.

26. Upon information and belief, O-Net's acts of infringing the '204 patent have been willful and in deliberate disregard of Optoplex's patent rights.

27. As a result of O-Net's infringement of the '204 patent, Optoplex has suffered and will continue to suffer damages.

SECOND COUNT
O-NET'S INFRINGEMENT OF U.S. PATENT NO. 7,522,343

28. Optoplex incorporates by reference paragraphs 1 through 27 above as though fully restated herein.

29. Optoplex is the sole owner by assignment of the '343 patent and possesses all rights of recovery under the '343 patent, including the right to sue for infringement and recover past damages.

30. Upon information and belief, O-Net has infringed and if not enjoined, will continue to infringe one or more claims of the '343 patent by performing, without authority, one or more of the following acts: (1) making, using, importing, offering for sale, or selling in the United States O-Net Devices that infringe one or more claims of the '343 patent, in violation of 35 U.S.C. §271(a); (2) inducing infringement of one or more claims of the '343 patent in violation of 35 U.S.C. §271(b); and/or (3) contributing to the infringement of one or more claims of the '343 patent in violation of 35 U.S.C. §271(c).

31. O-Net's acts of infringement of the '343 patent, literal and/or under the doctrine of equivalents, include making, using, offering to sell, or selling, in this District or elsewhere in the United States, O-Net Devices and/or other similar products that practice one or more claims of the '343 patent, including 10G/40G tunable DPSK/DQPSK Demodulator.

32. Upon information and belief, O-Net has induced and continues to induce infringement of one or more claims of the '343 patent in this District and elsewhere in the United

States, by, among other things, actively encouraging, or otherwise causing its customers to use O-Net Devices and/or other similar products that practice one or more claims of the '343 patent, such as 10G/40G tunable DPSK/DQPSK Demodulator.

33. Upon information and belief, O-Net has had knowledge of the '343 patent prior to the filing or upon service of the Complaint in this action, and continues to encourage, or otherwise cause its customers to use O-Net Devices and/or other similar products in a manner which infringes one or more claims of the'343 patent.

34. Upon information and belief, O-Net has specifically intended that its customers to use the accused products in such a way that infringes the '343 patent by, at minimum, providing datasheets, white papers, manuals and/or technical support to its customers on how to use the accused products in such a way that infringes the '343 patent.

35. Upon information and belief, O-Net has contributed to and continues to contribute to the infringement of one or more claims of the '343 patent by offering to sell, and selling to its customers, in this district and elsewhere in the United States, the accused products that constitute a material component of a device, system, combination or composition covered by the '343 patent, and that the customers have utilized said products in a manner that infringes one or more claims of the '343 patent.

36. Upon information and belief, O-Net has been aware, since at least the service of this action, that its products accused of infringement including, but not limited to, the accused products are especially made and/or adapted for use(s) that infringe one or more claims of the '343 patent and are, therefore not staple articles or commodities of commerce suitable for substantial non-infringing use.

37. Upon information and belief, O-Net's acts of infringing the '343 patent have been willful and in deliberate disregard of Optoplex's patent rights.

38. As a result of O-Net's infringement of the '343 patent, Optoplex has suffered and will continue to suffer damages

PRAYER FOR RELIEF

WHEREFORE, Plaintiff Optoplex asks this Court to enter judgment in its favor against

O-Net and grant the following relief:

1. An adjudication that O-Net has infringed, and continues to infringe, the '204 patent as alleged above;

2. An adjudication that O-Net has infringed, and continues to infringe, the '343 patent as alleged above

3. An accounting of all damages sustained by Optoplex as a result of O-Net's acts of infringement of the '204 and '343 patents;

4. An award to Optoplex of actual damages adequate to compensate Optoplex for O-Net's acts of patent infringement, together with prejudgment and post judgment interest;

5. An award to Optoplex of enhanced damages, up to and including trebling of Optoplex's damages pursuant to 35 U.S.C. § 284 for O-Net's willful infringement;

6. An award of Optoplex' s costs of suit and reasonable attorneys' fees pursuant to 35 U.S.C. § 285 due to the exceptional nature of this case, or as otherwise permitted by law;

7. A grant of a permanent injunction pursuant to 35 U.S.C. § 283, enjoining O-Net, and each of its agents, servants, employees, principals, officers, attorneys, successors, assignees, and all those in active concert or participation with O-Net, including related individuals and entities, customers, representatives, OEMs, dealers, and distributors from further acts of: (1) infringement, (2) contributory infringement, and (3) active inducement to infringe with respect to the claims of Optoplex's Patents, or in the alternative, a post-judgment royalty for post-judgment infringement;

8. Any further relief that this Court deems just and proper.

JURY DEMAND

Plaintiff Optoplex requests a jury trial on all issues triable to a jury in this matter.

Dated: November 26, 2012

Respectfully submitted,

By: [signature]

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Palo Alto, CA 94306
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Facsimile: 650.213.8158

ATTORNEYS FOR PLAINTIFF
OPTOPLEX CORPORATION

EXHIBIT A

US006587204B2

(12) **United States Patent**
Hsieh

(10) **Patent No.: US 6,587,204 B2**
(45) **Date of Patent: Jul. 1, 2003**

(54) **APPLICATION OF A STEP-PHASE INTERFEROMETER IN OPTICAL COMMUNICATION**

(75) Inventor: **Yung-Chieh Hsieh**, San Jose, CA (US)

(73) Assignee: **Optoplex Corporation**, Fremont, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 7 days.

(21) Appl. No.: **09/801,335**

(22) Filed: **Mar. 6, 2001**

(65) **Prior Publication Data**

US 2003/0081217 A1 May 1, 2003

Related U.S. Application Data

(60) Provisional application No. 60/258,427, filed on Dec. 27, 2000.

(51) **Int. Cl.**[7] **G01B 9/02**
(52) **U.S. Cl.** **356/450**; 359/124
(58) **Field of Search** 356/450; 359/124

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,169,626 B1 2/2001 Chen et al. 359/279
6,222,958 B1 * 4/2001 Paiam 356/491

OTHER PUBLICATIONS

Publication—"Optical Waves in Crystals" by Ammon Yariv and Pochi Yeh, p. 290–293.
Publication—"Optical Waves in Layered Media" by Pochi Yeh, p. 150.

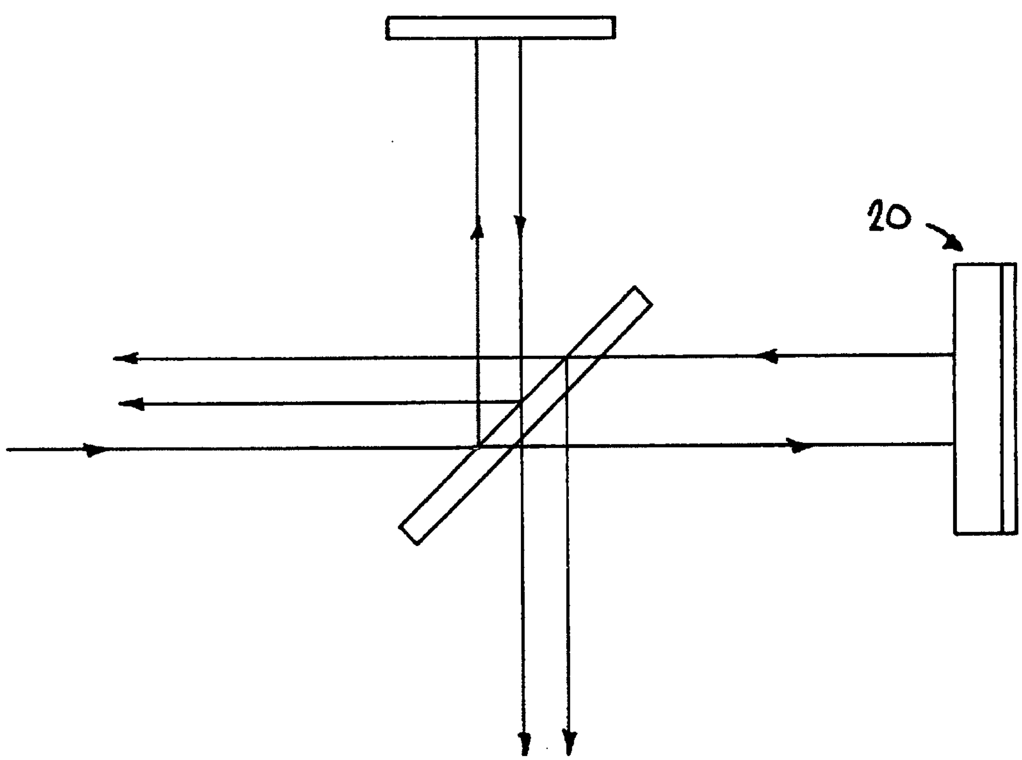
* cited by examiner

Primary Examiner—David V. Bruce
(74) *Attorney, Agent, or Firm*—John P. Wooldridge

(57) **ABSTRACT**

This invention is an optical communication interleave device using a variety of optical interferometer configurations where one of the beams carries a linear phase and the other beam carries a non-linear phase such that the frequency dependence of the phase difference between these two beams has a step-ike function. The present invention uses a variety of non-linear phase generators to generate this step like phase difference.

46 Claims, 12 Drawing Sheets



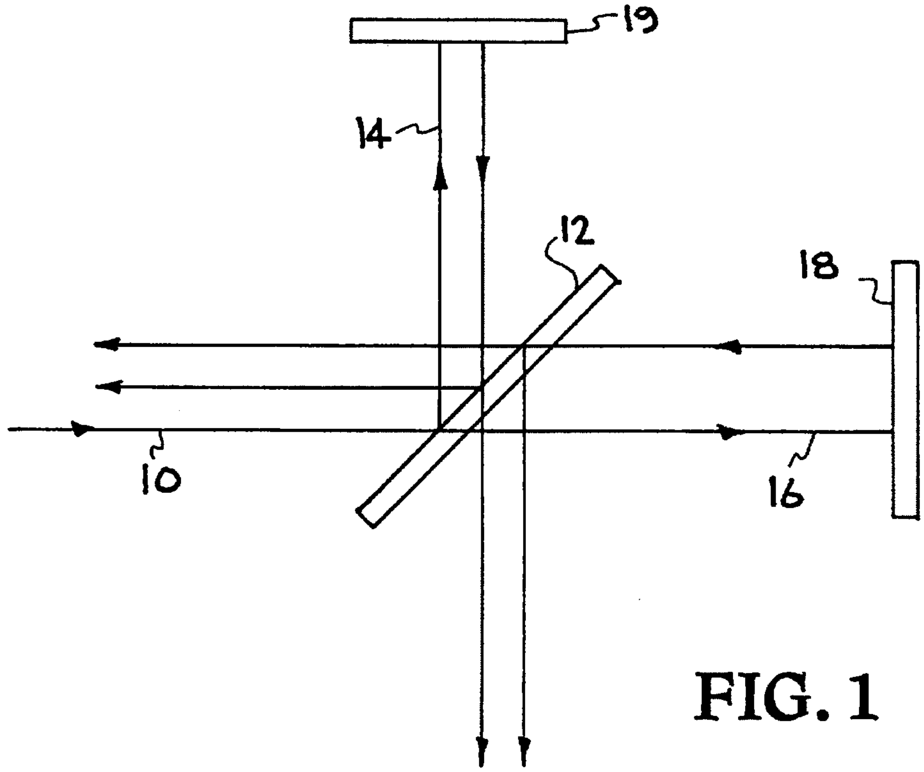

19
14
12
18
10
16

FIG. 1

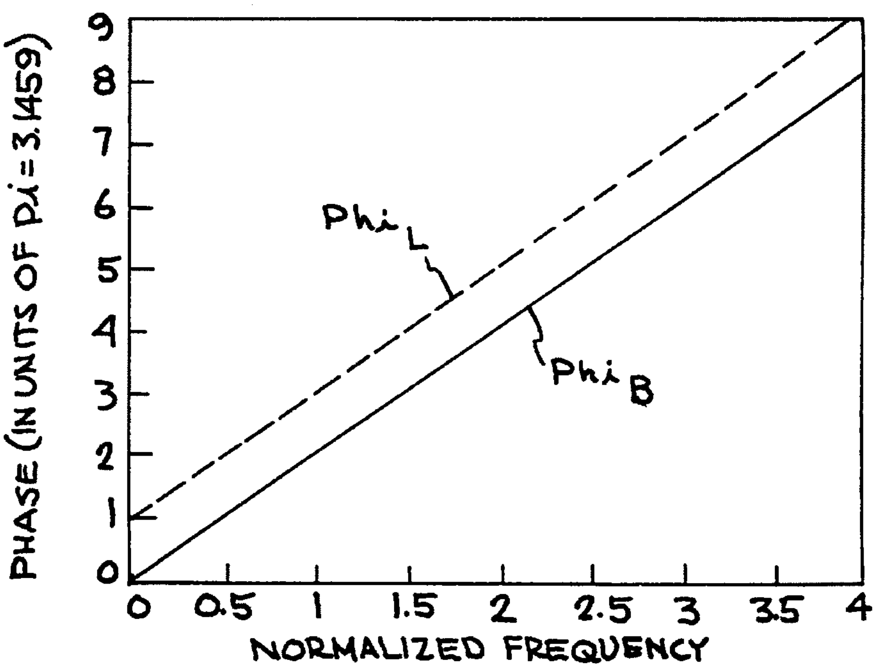

PHASE (IN UNITS OF Pi = 3.1459)
9
8
7
6
5
4
3
2
1
0
Phi L
Phi B
0
0.5
1
1.5
2
2.5
3
3.5
4
NORMALIZED FREQUENCY

FIG. 2

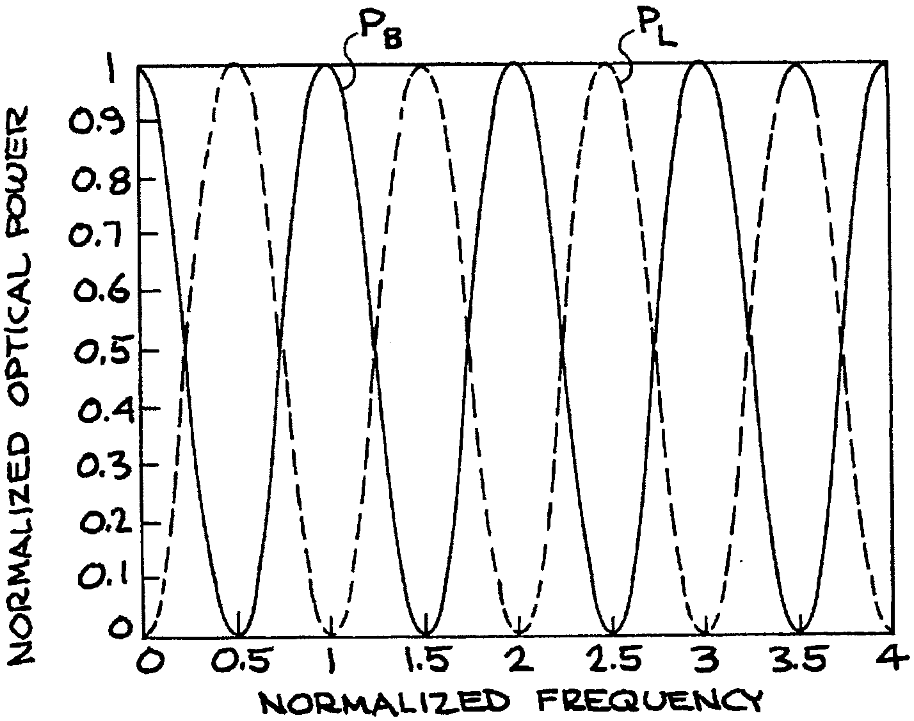

P_B
P_L
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
NORMALIZED OPTICAL POWER
0
0.5
1
1.5
2
2.5
3
3.5
4
NORMALIZED FREQUENCY

FIG. 3

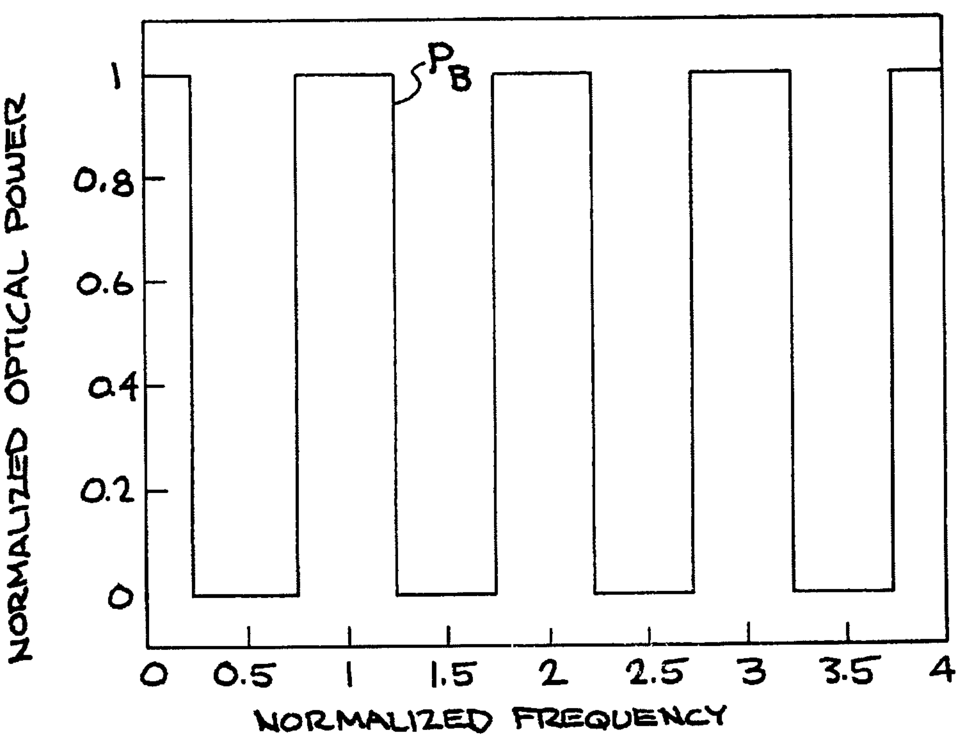
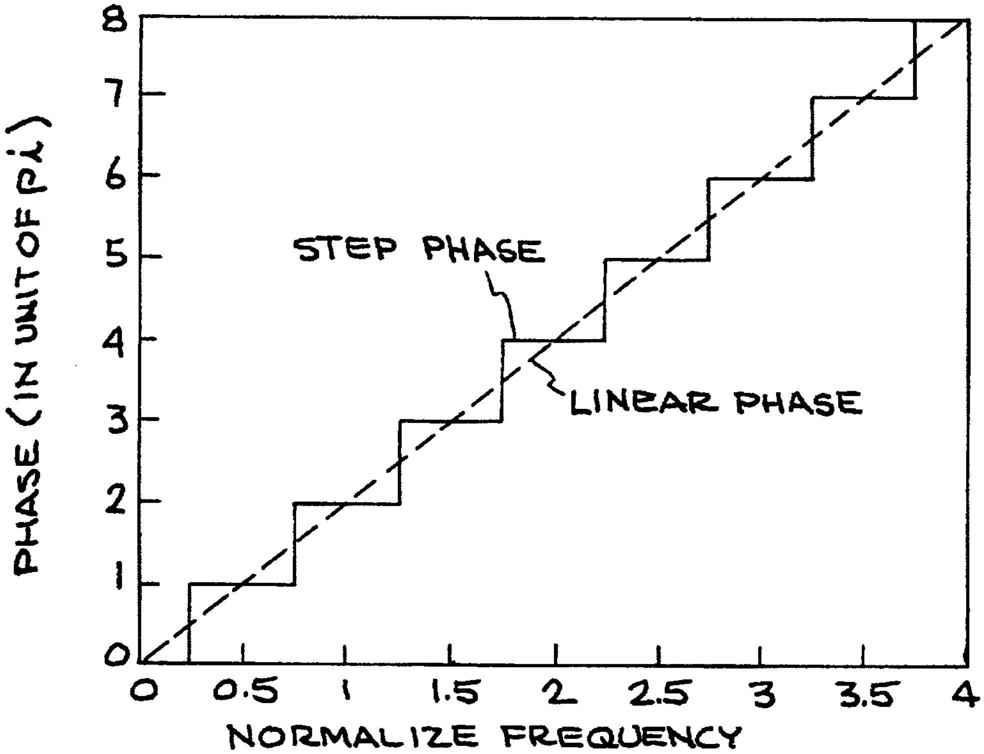
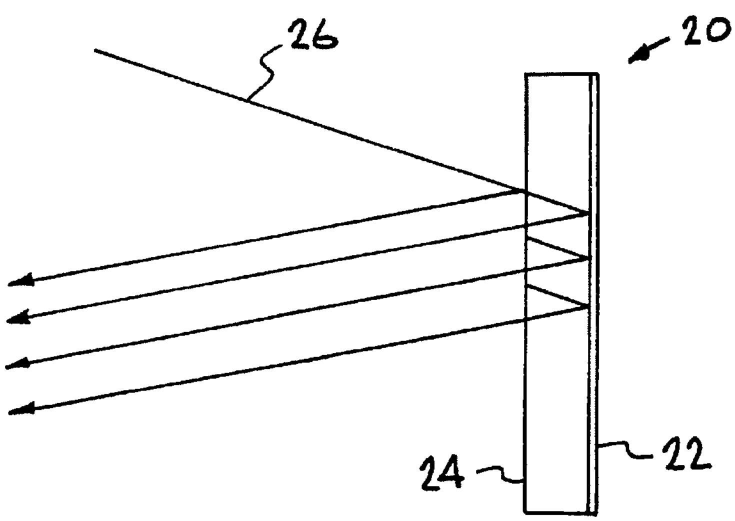

P_B
1
0.8
0.6
0.4
0.2
0
NORMALIZED OPTICAL POWER
0
0.5
1
1.5
2
2.5
3
3.5
4
NORMALIZED FREQUENCY

FIG. 4



PHASE (IN UNIT OF Pi)
0
1
2
3
4
5
6
7
8
STEP PHASE
LINEAR PHASE
0
0.5
1
1.5
2
2.5
3
3.5
4
NORMALIZE FREQUENCY

FIG. 5



26
20
24
22

FIG. 6

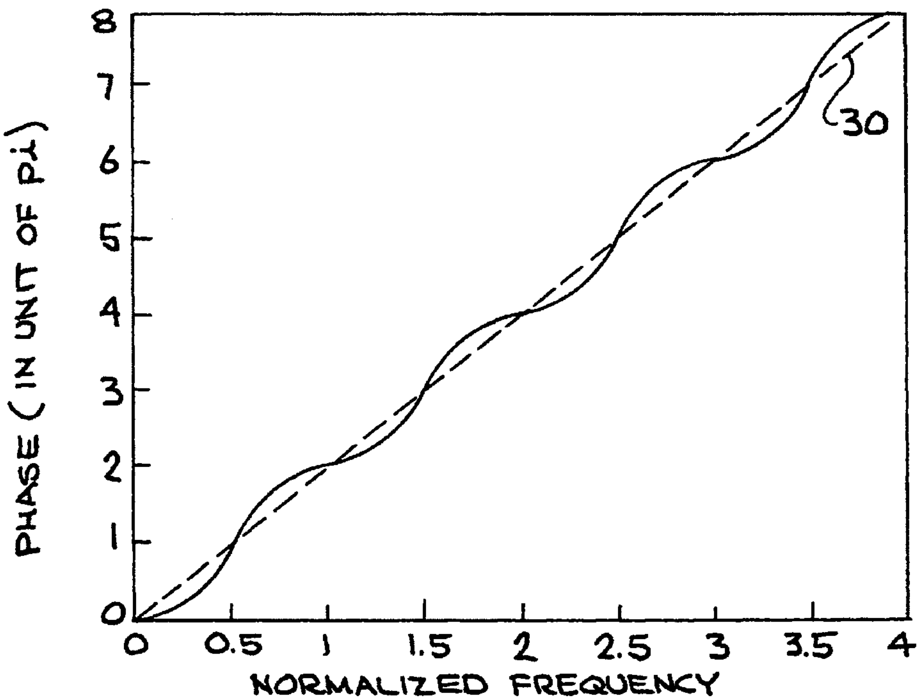

8
7
6
5
4
3
2
1
0
PHASE (IN UNIT OF Pi)
30
0
0.5
1
1.5
2
2.5
3
3.5
4
NORMALIZED FREQUENCY

FIG. 7A

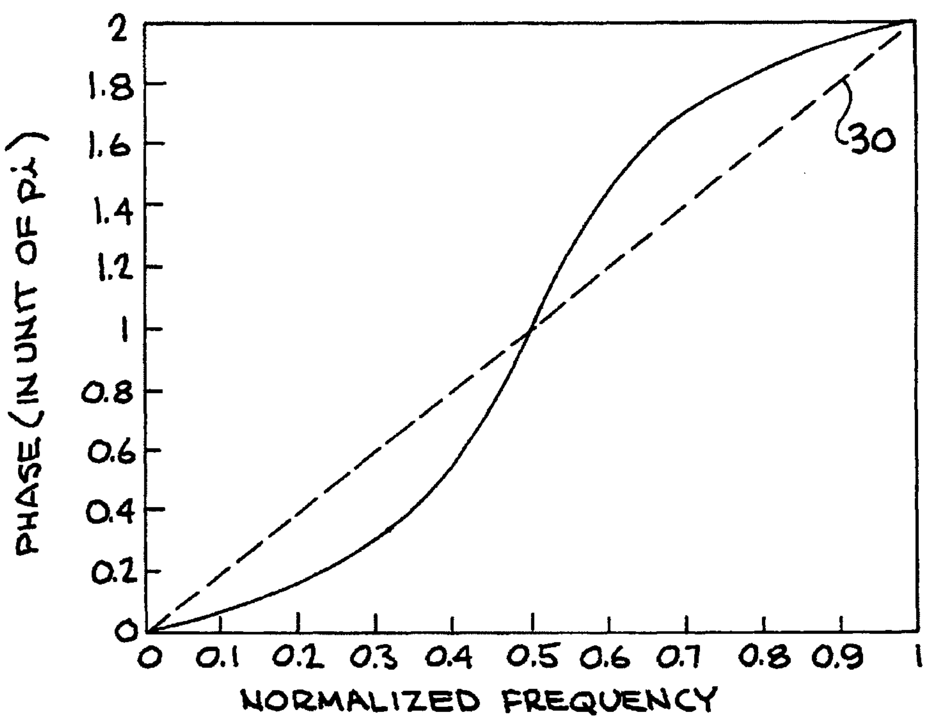

2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
PHASE (IN UNIT OF Pi)
30
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
NORMALIZED FREQUENCY

FIG. 7B

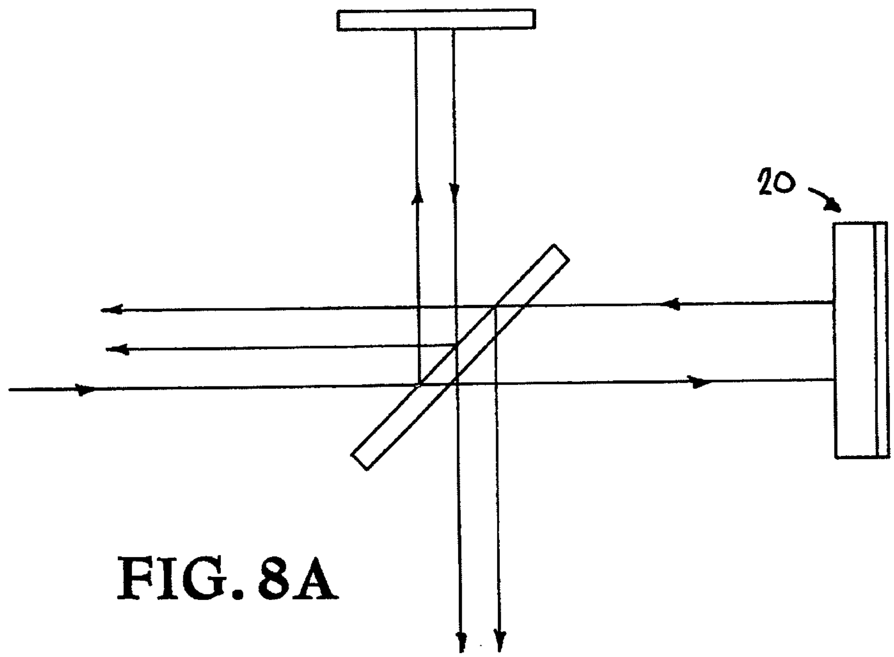


FIG. 8A

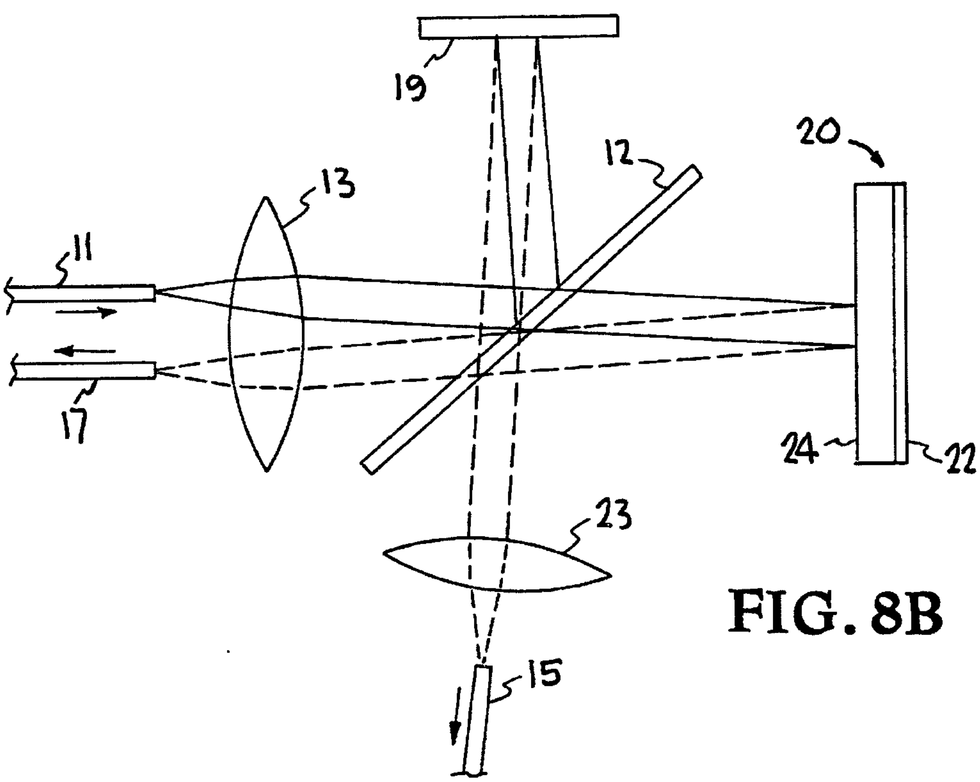


FIG. 8B

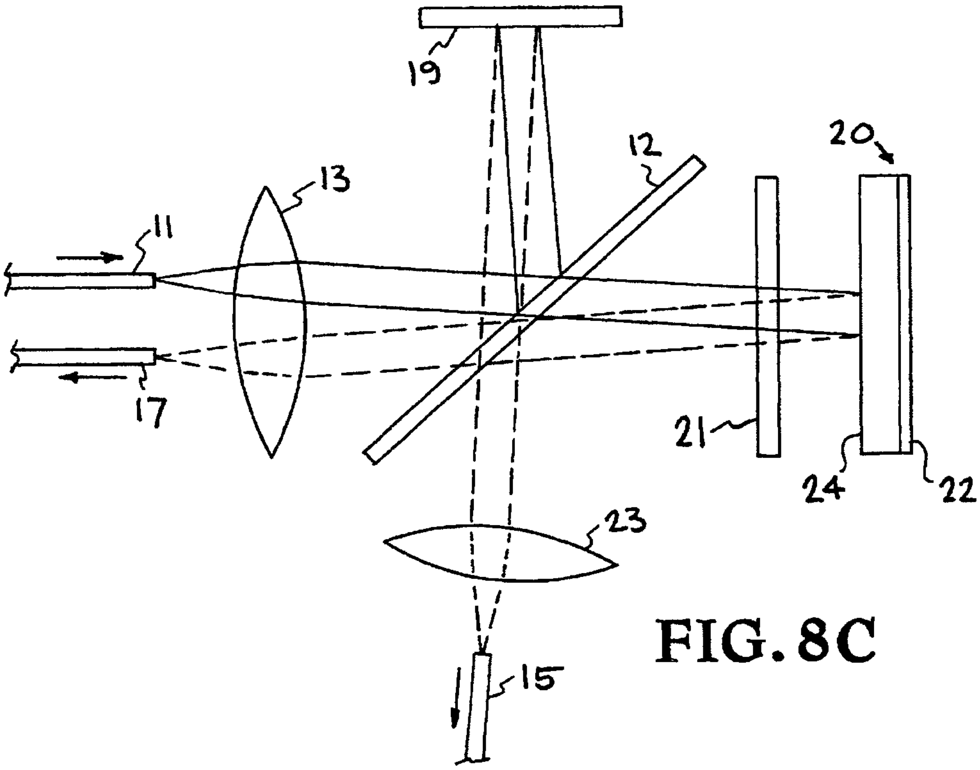

19
20
12
13
11
17
21
24
22
23
15

FIG. 8C

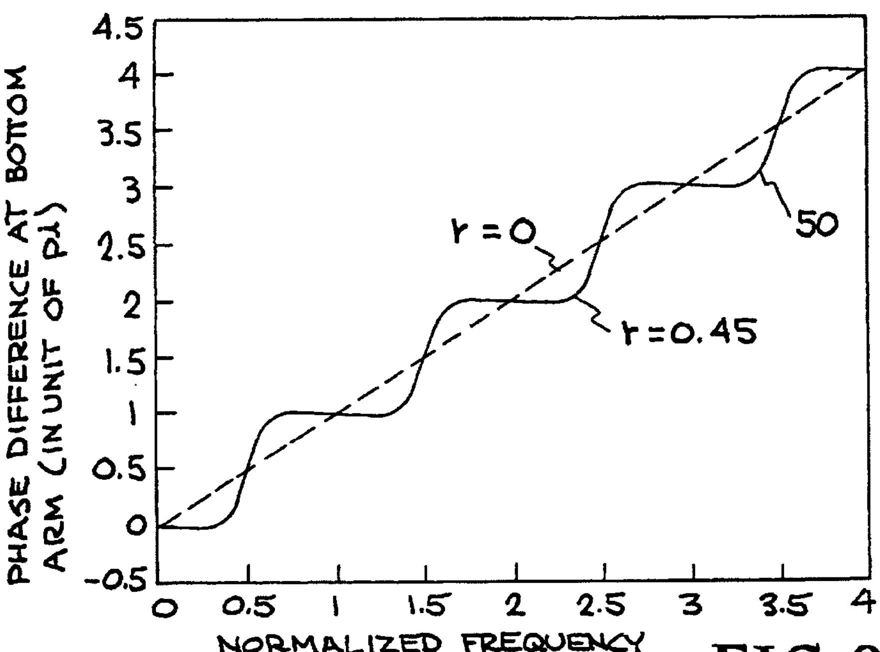

PHASE DIFFERENCE AT BOTTOM ARM (IN UNIT OF PI)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
NORMALIZED FREQUENCY
r = 0
r = 0.45
50

FIG. 9

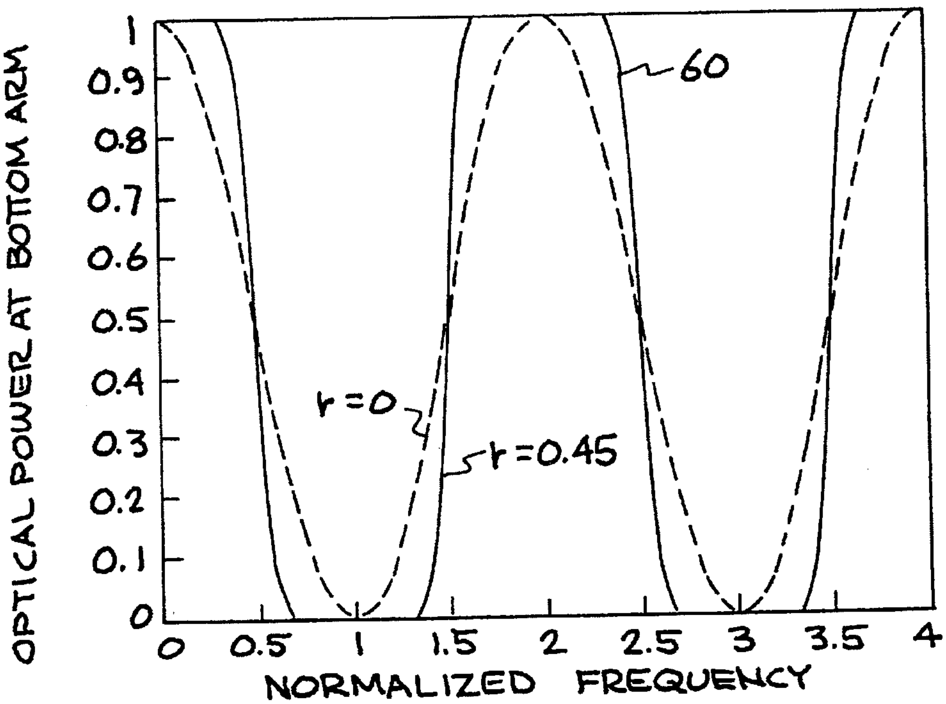

OPTICAL POWER AT BOTTOM ARM
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
3.5
4
NORMALIZED FREQUENCY
60
r=0
r=0.45

FIG. 10

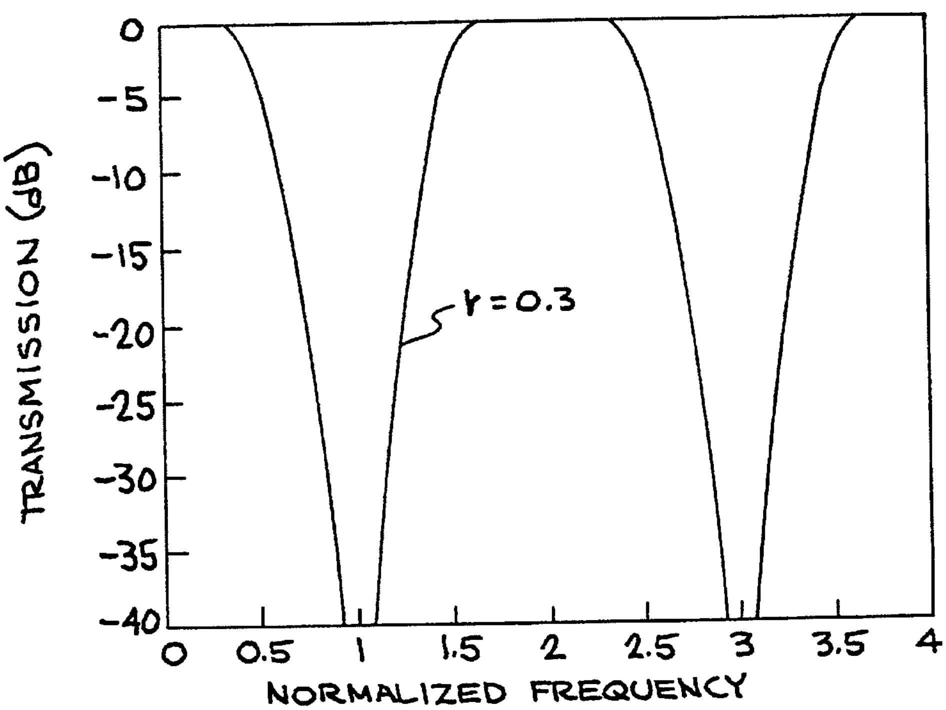
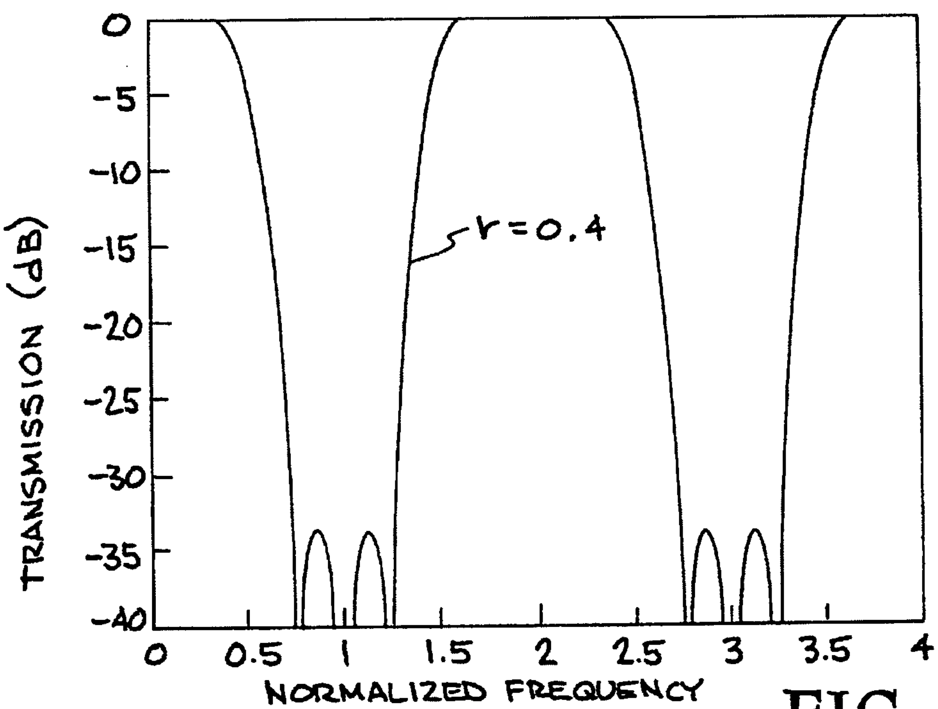
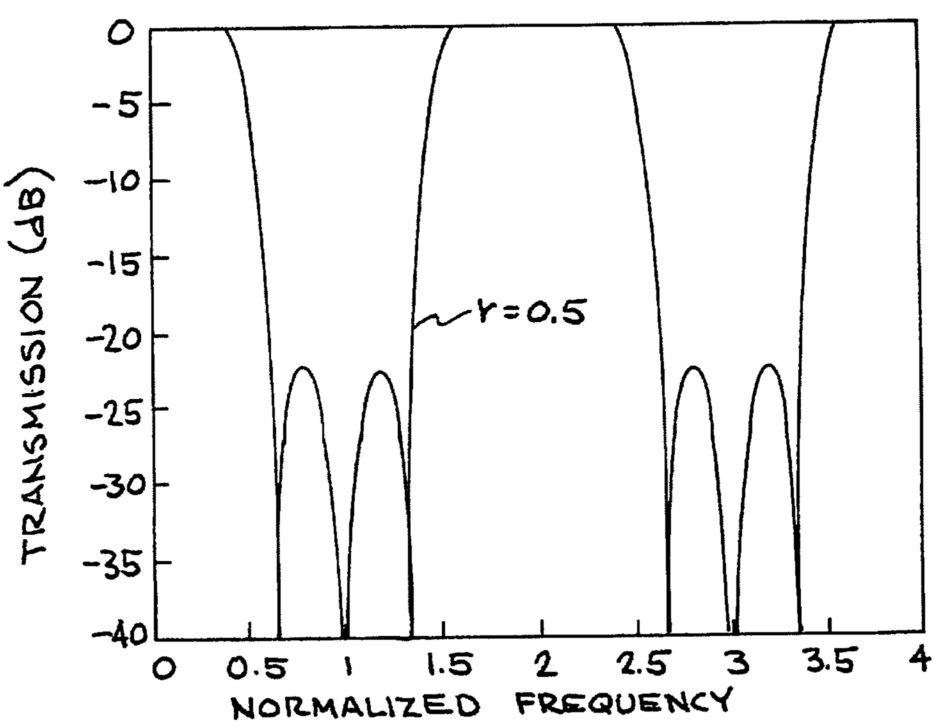

TRANSMISSION (dB)
0
-5
-10
-15
-20
-25
-30
-35
-40
0
0.5
1
1.5
2
2.5
3
3.5
4
NORMALIZED FREQUENCY
r=0.3

FIG. 11



TRANSMISSION (dB)
0
-5
-10
-15
-20
-25
-30
-35
-40
r=0.4
0
0.5
1
1.5
2
2.5
3
3.5
4
NORMALIZED FREQUENCY

FIG. 12



TRANSMISSION (dB)
0
-5
-10
-15
-20
-25
-30
-35
-40
r=0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
NORMALIZED FREQUENCY

FIG. 13

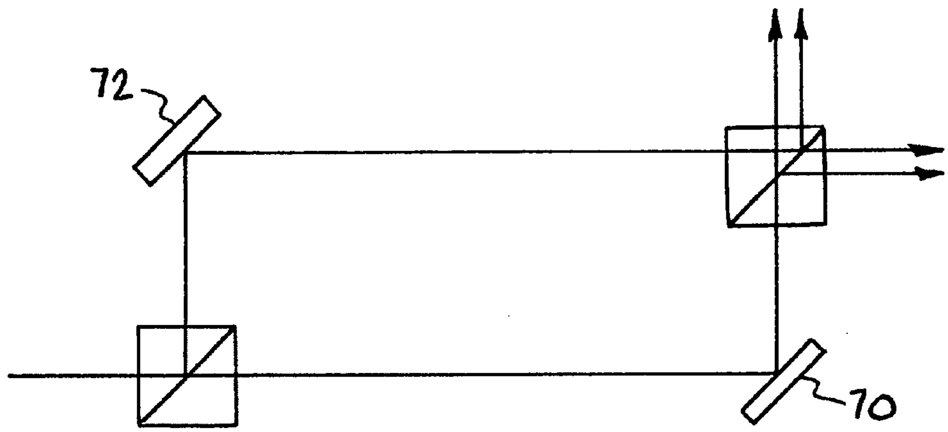


FIG. 14

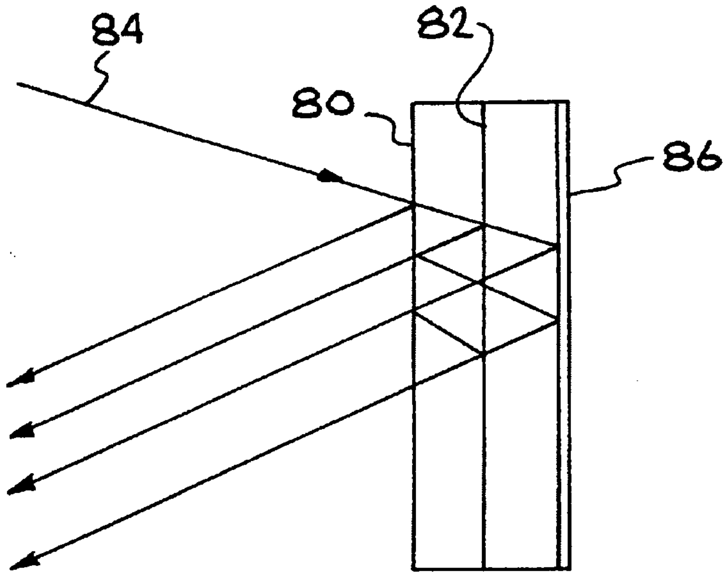
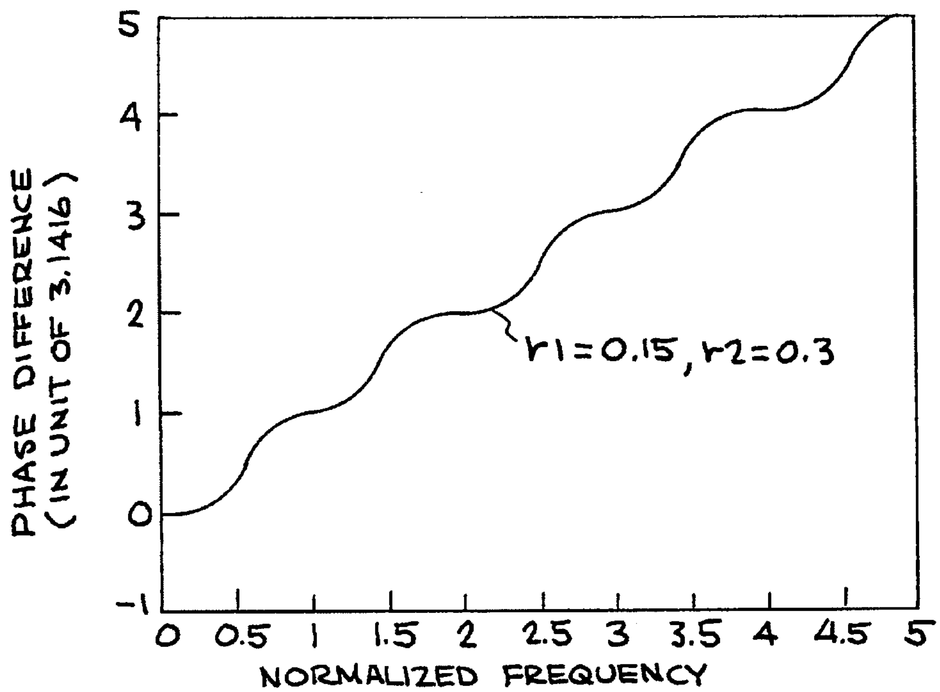
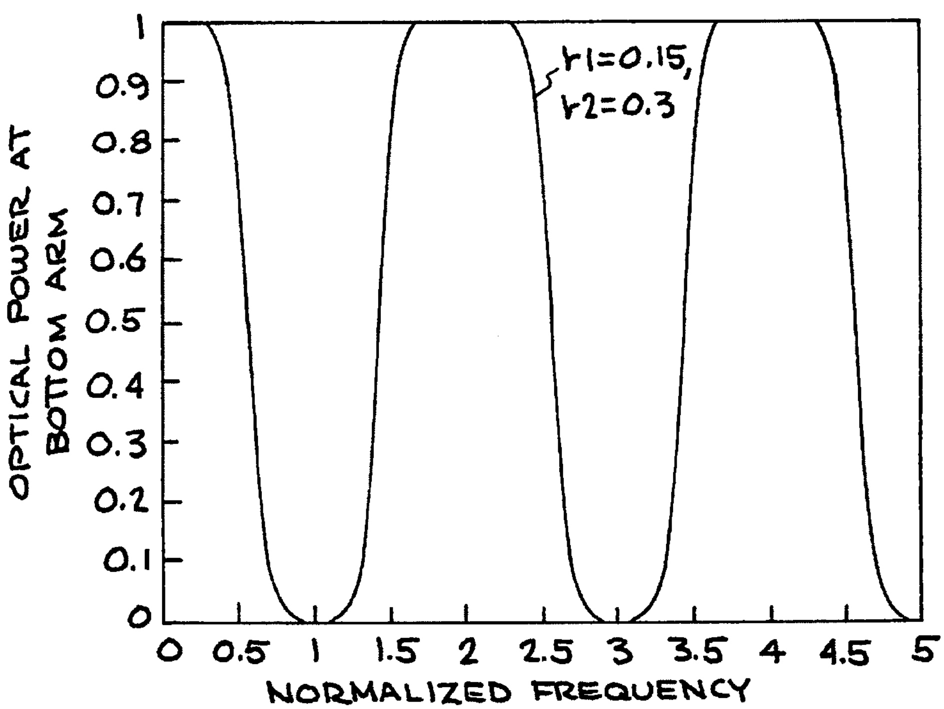


FIG. 15



PHASE DIFFERENCE (IN UNIT OF 3.1416)
5
4
3
2
1
0
-1
r1=0.15, r2=0.3
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
NORMALIZED FREQUENCY

FIG. 16



OPTICAL POWER AT BOTTOM ARM
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
r1=0.15,
r2=0.3
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
NORMALIZED FREQUENCY

FIG. 17

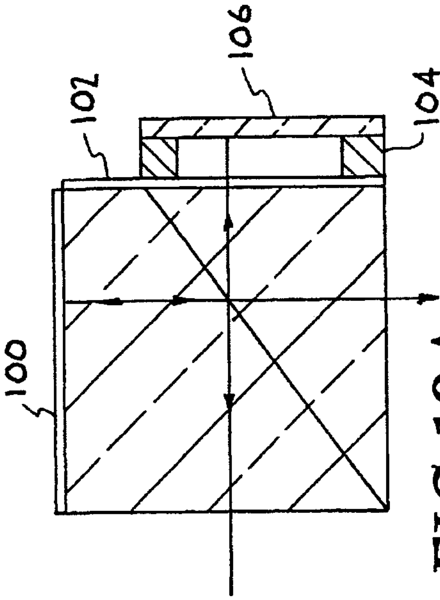


FIG.19A

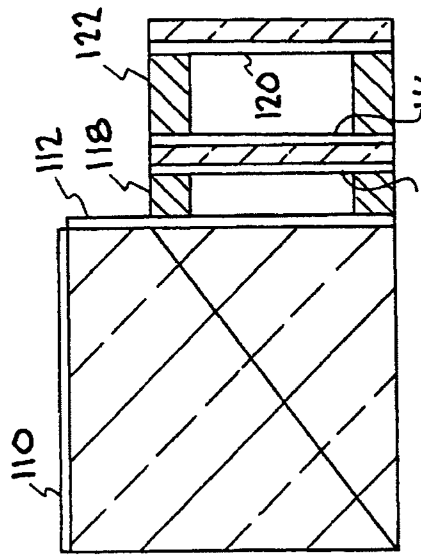


FIG.20

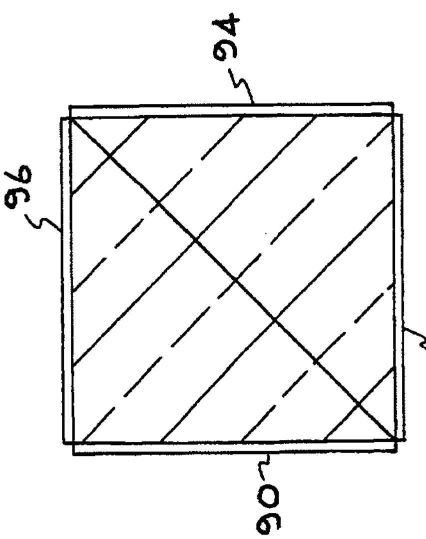


FIG.18

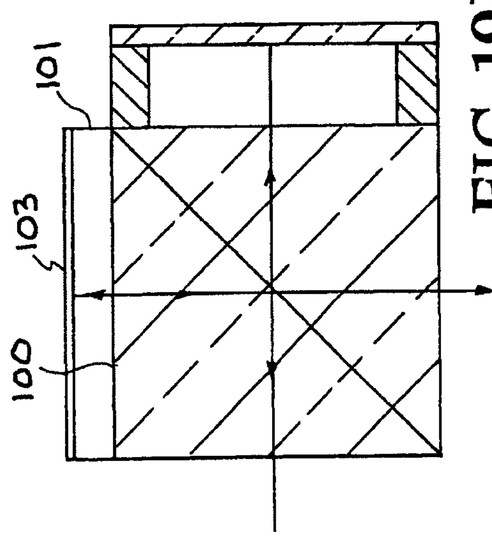


FIG.19B

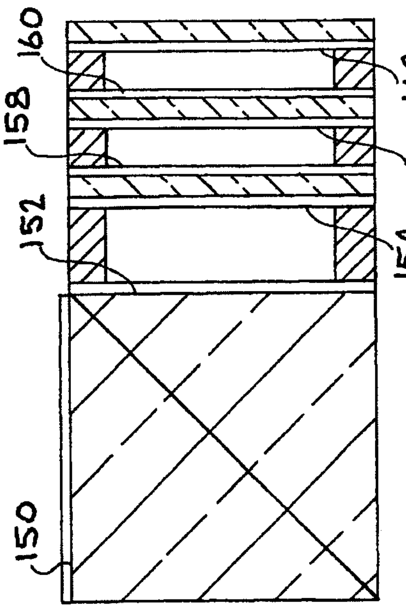


FIG. 22

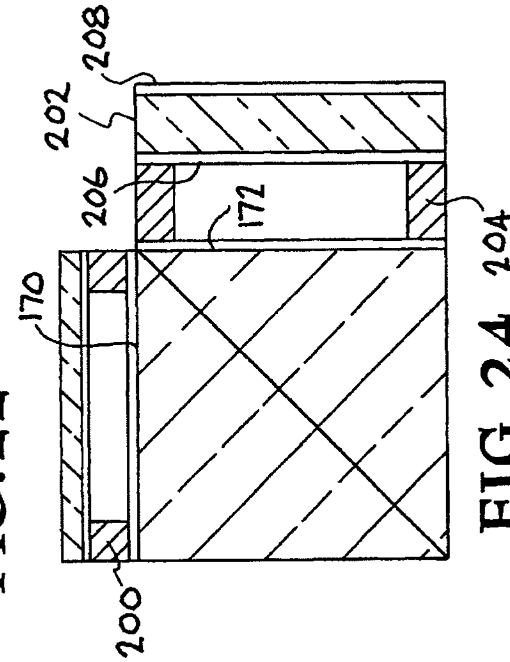


FIG. 24

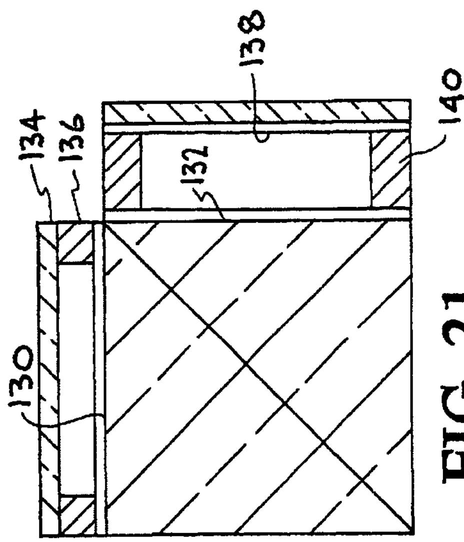


FIG. 21

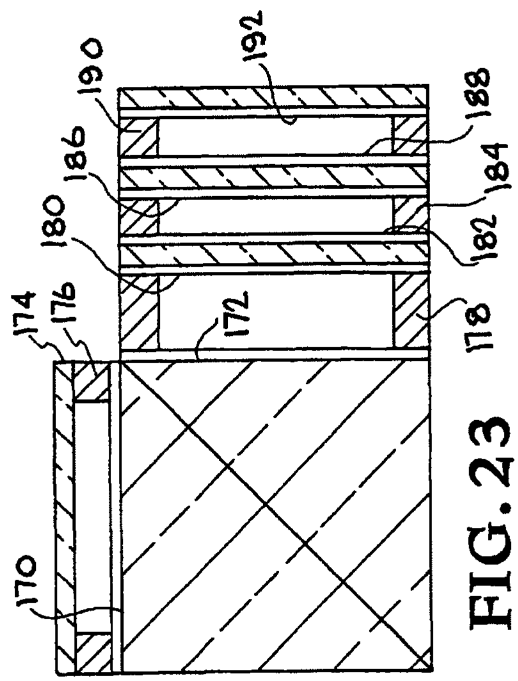


FIG. 23

APPLICATION OF A STEP-PHASE INTERFEROMETER IN OPTICAL COMMUNICATION

This application claims priority to Provisional Patent Application Serial No. 60/258,427, titled "The Application of Step-Phase Interferometer in Optical Communication" filed Dec. 27, 2000, incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to optical communication, and more specifically, it relates to methods and apparatuses for interleaving frequencies in optical communication systems.

2. Description of Related Art

In dense wavelength division multiplexing (DWDM) optical communication, various frequencies (wavelengths) of laser light are coupled into the same optical fiber. The information capacity is directly proportional to the number of channels in the fiber. Since the total usable wavelength range is limited (about a few tens of nanometers), the smaller the channel spacing, the more channels can fit into the same optical fiber, therefore enabling more communication capacity.

The minimum possible channel spacing is limited by the capability of the multiplexer (MUX) and the de-multiplexer (de-MUX). Currently, the standard channel spacing is 100 GHz (0.8 nm). The manufacturing costs increase dramatically when the channel spacing is less than 100 GHz. A cost-effective method is desirable for interleaving channels thereby enabling the use of higher bandwidth filters with lower channel spacing in an optical communication system. For instance, one can use 100 GHz filters with 50 GHz channel spacing for using a one-stage interleave. Furthermore, if a two-stage interleave is implemented, 100 GHz filters can be used in 25 GHz channel spacing communication system.

FIG. **1A** shows a conventional Michelson interferometer. The incident light **10** from the left-hand side of a 50—50 beam-splitter **12** is separated into two beams; 50% of the power is reflected from the beam splitter in beam **14** and the rest of light is transmitted in beam **16**. After those two beams are reflected from mirror **18** and mirror **19**, they are reflected by and transmitted through the beam-splitter again. The interference takes place at both the bottom and the left of the beam-splitter. The constructive interference takes place when the optical path length difference (OPD) of the two interference beams is an integer multiplication of wavelength. Since the total energy is conserved, the summation of optical power at the bottom arm and the left arm should be equal to the optical power delivered from the light source. In other words, when the constructive interference occurs at the bottom arm, the destructive interference should take place at the left arm and vise verse.

For the interferometer shown in FIG. **1**, the amplitudes of the two interference beams are the same and their phase difference depends on the OPD. The various phase functions are listed in Table 1.

Table 1

Definition of Phase

$\psi_{RTM'}$:reflected by BS→reflected by mirror→transmit through BS.

$\psi_{TMR'}$:transmitted through BS→reflected by mirrors→reflected by BS.

ψ_{RMR}:reflected by BS→reflected by mirror→reflected by BS

ψ_{TMT}:transmitted by BS→reflected by mirror→transmit through BS

ψ_{ST}:phase introduced by the BS for S-polarized light, transmitted beam with front side incidence

$\psi_{ST'}$:phase introduced by the BS for S-polarized light, transmitted beam with rear side incidence

ψ_{SR}:phase introduced by the BS for S-polarized light, reflected beam with front side incidence

$\psi_{SR'}$:phase introduced by the BS for S-polarized light, reflected beam with rear side incidence

ψ_{PT}:phase introduced by the BS for P-polarized light, transmitted beam with front side incidence

$\psi_{PT'}$:phase introduced by the BS for P-polarized light, transmitted beam with rear side incidence

ψ_{PR}:phase introduced by the BS for P-polarized light, refleced beam with front side incidence

$\psi_{PR'}$:phase introduced by the BS for P-polarized light, reflected beam with rear side incidence

$\psi_B=\psi_{TRM'}-\psi_{RMT}$(phase difference of the two interference beams in the bottom arm)

$\psi_L=\psi_{TMT'}-\psi_{RMR}$(phase difference of the two interfereince beams in the left arm)

Power Definition

P_B:optical power in the bottom arm

P_L: optical power in the left arm

Assuming that the incident polarization is S-polarized, the two electric fields at the bottom arm can be expressed as follows.

$$\vec{E}_{TMR'}=\frac{\hat{s}}{2}\exp(i\Psi_{TMR'})$$

$$\vec{E}_{RMT}=\frac{\hat{s}}{2}\exp(i\Psi_{RMT})$$

The power at the bottom arm is as follows.

$$P_B=\left\|\vec{E}_{TMR'}+\vec{E}_{RMT}\right\|^2=\left\|\hat{s}\cos\left[\frac{\psi_{TMR'}-\psi_{RMT}}{2}\right]\right\|^2=\cos^2\left(\frac{\psi}{2}\right)\quad\text{Equation (1)}$$

With

$$\psi_{TMR'}=2\pi\left(\frac{\nu}{\nu_1}\right)+\psi_{ST}+\psi_{SR'}\quad\text{Equation (2.1)}$$

$$\psi_{RMT}=2\pi\left(\frac{\nu}{\nu_2}\right)+\psi_{SR}+\psi_{ST}$$

$$\psi_B=\psi_B^{(s)}\equiv\psi_{TMR'}-\psi_{RMT}=2\pi\left(\frac{\nu}{\nu_0}\right)+(\psi_{SR'}-\psi_{SR})$$

where

$$\nu_1=\frac{C}{2L_1};\quad \nu_2=\frac{C}{2L_2};\quad \nu_0=\frac{C}{2(L_1-L_2)}$$

In Equation (1), the total power on the bottom arm is dependant on the phase difference between the two interference beams.

When the incident polarization is P-polarized,

$$\psi_B=\psi_B^{(p)}\equiv\psi_{TMR'}-\psi_{RMT}=2\pi\left(\frac{\nu}{\nu_0}\right)+(\psi_{PR'}-\psi_{PR})\quad\text{Equation (2.2)}$$

The phase difference of the two interference beams at the bottom arm for S-polarized light, $\psi^{(s)}_B$, and that of P-polarized light, $\psi^{(P)}_B$, will be the same when $\Psi_{SR}-\Psi_{SR'}=$

$\Psi_{PR}-\Psi_{PR'}$. In the following analysis at this section, it is assumed that the coating of beam splitter has been made such that $\Psi_{SR}-\Psi_{SR'}=\Psi_{PR}-\Psi_{PR'}=0$. Under such condition, $\psi_B=\psi^{(s)}_{B-\psi}{}^{(P)}_B$. Notice that in the derivation of equations (2.1) and (2.2), the phase introduced from the two reflection mirrors is neglected. Those phases do not have polarization dependence due to the fact that the incident angles at those surfaces are close to normal.

FIG. 2 shows the phase difference ψ_B and ψ_L. Both of them are a linear function of frequency with slope 2 Hv^{-1}_o. As a result of energy conservation, there is a phase offset π between them. FIG. 3 shows the corresponding optical power at the bottom (upper curve at 0 normalized frequency) and left arm (bottom curve at 0 normalized frequency). In these plots, the horizontal axis is normalized by frequency v_o. When the normalized frequency is an integer, all the light goes to the bottom; In contrast, as that is a half integer, the light goes to the left In other world, the light is interleaved in the frequency domain with half of the channels (integer frequency) to the bottom arm and the other half to the left arm.

The Michelson interferometer shows the fundamental requirement of interleaving. However, it is not practical to apply such an interferometer to a real interleave device since it is too sensitive to the central frequency and the line width of light source. Referring to FIG. 3, as the frequency is slightly off from the integer, part of the optical power will leak from the bottom arm towards the left arm, causing cross talk between channels. In other words, in order to make this device work, the laser line width should be zero and its central frequencies have to be perfectly locked over all the operation condition. Such frequency locking is very hard to achieve in the real world.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide an optical filtering method to separate/merge the odd and even channels in an optical communication system.

It is another object of the invention is to provide and optical interleaver that utilizes an interferometer where one beam carries a linear phase and the other beam carries a non-linear phase such that the frequency dependence of the phase difference, ψ_B, between these two arms has a step-like function

Still another object of the invention is to provide an optical interleaver that enables the use of higher bandwidth filters to have lower channel spacing communication system.

Another object of the invention is to provide optical interleaver methods and apparatuses that cost much less than existing interleaver devices and perform better.

These and other objects of the invention will be apparent to those skilled in the art based on the teachings herein.

This invention is an interleave device using an optical interferometer where one of the beams carries a linear phase and the other beam carries a non-linear phase such that the frequency dependence of the phase difference between these two arms has a step-like function. The present invention uses a non-linear phase generator (NLPG) to make the phase a non-linear function of optical frequency.

In one embodiment, a non-linear phase generator is a mirror made by a cavity. A first surface of the cavity has reflectivity less than one and the second reflection surface has reflectivity near 100%. As the light is incident onto the NLPG, it undergoes multiple reflections. When the static state is achieved, the amplitude of reflected light should be near 100% since the second reflecting surface reflects all of the incident optical power. The phase of the reflected light depends on the frequency of light and the physical properties of the cavity. For non-zero reflectivity of the first surface, the multiple reflections cause the phase to be a non-linear function of frequency.

In one embodiment of the invention, a modified Michelson interferometer, replaces a mirror with a cavity. The phase of the light beam reflecting from the cavity is a non-linear function of optical frequency. The phase of the other beam is a linear function of optical frequency. The dependence of the phase difference of these two beams on optical frequency is a step-like function with step H.

The polarization dependent feature of phase of each beam can result in certain problems. When the phase difference has polarization dependence, the interference fringe will peak at different frequencies. Therefore, when the incident polarization includes both P and S, the fringe contrast will be degraded. Secondly, when the transmission curve is perfect for the S-polarized light, the phase offset in the P-polarized light worsens the performance of the channel isolation. The present invention provides several techniques for compensating for the polarization dependent feature of phase of each beam. This disclosure provides examples of a variety of embodiments of step-phase interferometers usable in the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a conventional Michelson interferometer, consisting of a beam splitter (BS) and two reflection mirrors, M1 and M2.

FIG. 2 shows the phase difference, Ψ_B, of the two interference beams at the bottom arm, and the phase difference, Ψ_L, at the left arm as a function of normalized frequency.

FIG. 3 shows the optical power at the bottom and left arms as a function of normalized optical frequency.

FIG. 4 shows the optical power at the bottom arm for an ideal interleave device.

FIG. 5 shows the phase difference of the two interference beams, Ψ_B, at one of the output ports of an ideal interleave device.

FIG. 6 shows a non-linear phase generator, consisting of two surfaces. The first surface has amplitude reflectivity of less than 1, usually between 0.3 to 0.6, and the second surface has the reflectivity close to 1.

FIG. 7A shows the phase of the return beam from a non-linear phase generator as a function of normalized optical frequency for amplitude reflectivities of 0 (dash) and 0.45(solid).

FIG. 7B is an expanded view of FIG. 7A for the normalized optical frequency within the range from 0 to 1.

FIG. 8A shows an embodiment of a modified Michelson interferometer used as a step-phase interferometer.

FIG. 8B shows an embodiment of an interleave device used as a demultiplexer. The input fiber **11** contains all the wavelengths. After interference, the light of odd wavelengths goes to output fiber **1** (fiber **17**) and that of even wavelengths goes output fiber **2** (fiber **15**). This device can also be used as a multiplexer by sending light of even wavelengths through fiber **15** and light of odd wavelengths through fiber **17**. After interference, all the light will come out from fiber **11**.

FIG. 8C shows a phase retardation plate placed in the right arm to generate a required phase difference between P- and S-polarized light.

FIG. **9** shows the phase difference of the two interference beams at the bottom arm, Ψ_B for r=0 (dashed) and 0.45 (solid).

FIG. **10** is the optical power at the bottom arm for r=0 (dashed) and 0.45 (solid).

FIG. **11** shows the optical power at the bottom arm for r=0.3 in the logarithm scale.

FIG. **12** is the optical power at the bottom arm for r=0.4 in the logarithm scale.

FIG. **13** is the optical power at the bottom arm for r=0.5 in the logarithm scale.

FIG. **14** shows a Mach-Zehnder type step-phase interferometer where the right arm is a regular mirror to create a linear phase and the cavity at the top arm is a non-linear phase generator.

FIG. **15** shows another type of non-linear phase generator, consisting of three reflection surfaces where the first two surfaces partially reflect the incident beam (with amplitude reflectivity of r**1** and r**2**) and the third surface has amplitude reflectivity close to 1.

FIG. **16** shows the phase difference, Ψ_B, of the two interference beams at one of the output arm for a step-phase interferometer with a three surface non-linear phase generator (such as shown in FIG. **15**), of r1=0.15, r2=0.3.

FIG. **17** shows the optical power at one of the output arms for a step-phase interferometer with a three-surface non-linear phase generator (the corresponding phase difference is shown in FIG. **16**).

FIG. **18** shows an un-polarized 50/50 beam splitter where the light is to be incident from the left hand side. The left side and the bottom side of the beam splitter are AR-coated; the right side can be AR or partially reflecting (PR) coated and topside can be AR or mirror coated, depending on which scheme is being used.

FIG. **19**A shows an embodiment where the topside of cube is coated as a mirror to generate a linear phase and the right-hand side of cube is PR coated to be surface **1** of a non-linear phase generator.

FIG. **19**B shows the top mirror of FIG. **19**A as an extra piece.

FIG. **20** shows an embodiment where the topside of cube is mirror coated to generate a linear phase, the right-hand side of cube is AR coated and the PR coating of the non-linear phase generator is an extra piece.

FIG. **21** is an embodiment where the topside of the cube is AR coated, the right-hand side of the cube is PR coated to be first surface of a non-linear phase generator and the mirror on the topside of cube is an extra piece.

FIG. **22** shows an embodiment where the topside of the cube is mirror coated to be a linear phase generator, the right-hand side of cube is AR coated and the non-linear phase is achieved by an external three-surface cavity.

FIG. **23** shows an embodiment where the topside and right-hand side of the cube are AR coated and the mirror for a linear phase generator and the three-surface non-linear phase generator are two external pieces.

FIG. **24** shows and embodiment where the topside and right-hand side of the cube are AR coated and the mirror for a linear phase generator and the two-surface non-linear phase generator consisting of glass cavity are two external pieces.

DETAILED DESCRIPTION OF THE INVENTION

This invention proposes to make an interleave device using an optical interferometer where one of the beams carries a linear phase and the other beam carries a non-linear phase such that the frequency dependence of the phase difference between these two interference beams at the bottom arm, ψ_B, has a step-like function with step π. Under this condition, the frequency dependence of phase difference between the two interference beams at the left arm, ψ_L, also has the same step-like function but offset vertically by π, as a result of energy conservation

FIG. **4** shows the transmission curve of bottom arm for an ideal interleave device. In order to have such transmission curve, the frequency dependence of phase difference between RMT and TMR' should be, e.g., as shown in FIG. **5** where the phase difference should be equal to 2 Π in the frequency range of 0.75 to 1.25 (the neighborhood of 1) and equal to Π in the range of 0.25 to 0.75 (the neighborhood of 0.5), and so on. The flat top behavior is an important characterization of any interleave device, since it is directly related to the usable bandwidth and the isolation between adjacent channels.

In order to generate a step like phase difference, ψ_B, one has to rely on a non-linear phase generator. FIG. **6** shows an embodiment of a non-linear phase generator that is a "mirror" **20** made by a cavity. The right-hand surface **22** of the cavity has power reflectivity near 100% and the left-hand surface **24** of the cavity has a power reflectivity that is less than one. As the light **26** is incident from the left-hand side, it undergoes multiple reflections. When the static state is achieved, the amplitude of reflected light should be near 100% since the second reflection surface reflects the entire optical power incident thereon. The phase of the reflected light depends on the frequency of light and the physical properties of the cavity. The phase can be expressed as follows. See "Optical Waves in Crystals" by Amnon Yariv and Pochi Yeh, page 290–293. See also "Optical Waves in Layered Media" by Pochi Yeh, page 150.

$$\psi_c = 2\tan^{-1}\left[\alpha\tan\left(\pi\frac{v}{v_c}\right)\right]$$

$$\alpha = \frac{1-r}{1+r}$$

$$v_c = \frac{C}{2n_cL_c}$$

Equation (3) neglects the phase-introduced by the two reflection surfaces. Taking that into account will not add complexity to the analysis but will linearly shift Ψ_C in Equation (3). FIGS. **7**A and **7**B show the phase of reflected light from such a cavity for the amplitude reflectivity of the left surface **24** of FIG. **6**, r, equal to 0 and 0.45. Notice that the horizontal axis is normalized by frequency v_c. For r=0, it is a linear curve **30** corresponding to the phase shift of light traveling a distance of $2L_c$. For non-zero r, the multiple reflections have to be taking into account, causing the phase to be a non-linear function of frequency. FIG. **8**A shows a step-phase interferometer, modified from a Michelson interferometer, where mirror M1 (**18** in FIG. **1**) is replaced by a cavity **20** shown in FIG. **6**. The two electric field at the bottom arm are as follows. (Assuming that the incident beam is S-polarized)

$$\vec{E}_{TCR'} = \frac{\hat{s}}{2}\exp(i\psi_{TCR'})$$

-continued

$$\vec{E}_{RMT} = \frac{\hat{s}}{2}\exp(i\psi_{RMT})$$

Where

$$\psi_{TCR'} = 2\pi\left(\frac{\nu}{\nu_1}\right) + \psi_c + \psi_{ST} + \psi_{SR'}$$

$$\psi_{RMT} = 2\pi\left(\frac{\nu}{\nu_2}\right) + \psi_{SR} + \psi_{ST}$$

The total energy at the bottom arm is expressed as follows.

$$P_B = \left\|\vec{E}_{TCR'} + \vec{E}_{RMT}\right\|^2 = \cos^2\left(\frac{\psi_B^{(s)}}{2}\right)$$

where

$$\psi_B^{(s)} = \psi_c + 2\pi\left(\frac{\nu}{\nu_0}\right) + (\psi_{SR'} - \psi_{SR})$$

The first term in Equation (5) is a non-linear phase coming from the cavity. When $v=mv_c$, where m is an integer, one has $\Psi c=2\ m\pi$. On the other hand, the second term of Equation (5) is a linear phase from the optical path difference between two arms. With $v=mv_0$, the linear phase is $2m\pi$. The third term in equation (3) is the phase generated by the beam splitter coating. In general, it is polarization dependant When the beam splitter is coated symmetrically, this term goes to zero (since it makes no difference for the beam being incident from the front side of the beam splitter or rear side of the beam splitter). Under such condition, the phase difference between the two interference beams at bottom arm is not dependant on the incident polarization. In the following analysis, the third term is set to zero.

Back to equation (5), to have a phase step of π for Ψ_B, one has to set $v_0=-2v_c$, yielding

$$\psi_B = \psi_c - \pi\frac{\nu}{\nu_c} = 2\tan^{-1}\left[\alpha\tan\left(\pi\frac{\nu}{\nu_c}\right)\right] - \pi\frac{\nu}{\nu_c}$$

$$\psi_B = \begin{cases} 0, & \text{for } \nu = 2m\nu_c \\ \pi, & \text{for } \nu = (2m+1)V_c \end{cases}$$

To make the phase difference Ψ_B like a step function shown in FIG. 5, the slope of Ψ_B near the multiple integer of v_c should be close to zero.

$$\frac{d\psi_B}{d\nu} \to 0 \text{ as } \nu = m\nu_c$$

$$\Rightarrow \alpha \approx 0.5 \text{ (corresponding to } r \approx 0.33)$$

If the third term in equation (5) is not zero and its value is dependant on the polarization of the incident beam, it can result in certain problems. Firstly, the optical signal at bottom arm will peak at different frequencies for different polarizations. Therefore, when the incident polarization includes both P and S, the fringe contrast will be degraded. Secondly, when the transmission curve is perfect for the S-polarized light (like FIG. 4), the phase offset in the P-polarized light worsens the performance of the channel isolation. To make Ψ_B polarization independent, one has to design the internal beam splitting coating of the beamsplitter (BS) such that $\Psi_{SR}-\Psi_{SR'}=\Psi_{PR}-\Psi_{PR'}$. One of the choices is to make the coating symmetric, which means the beam will see the same layer structure whether it is incident from the

front side or the rear side. Such condition guarantees that $\Psi_{SR}=\Psi_{SR'}$ and $\Psi_{PR}=\Psi_{PR'}$ at all times. Other than this, one can place a phase retardation plate in the optical path to compensate the phase difference between P- and S-polarized light

FIG. **8B** shows an interleave device used as a demultiplexer. It consists of three components, (i) a beam splitter **12**, (ii) a reflection surface **19** and a cavity **20**. In this example, the cavity is composed of an air-gap sandwiched by two pieces of reflection surfaces (shown in FIG. **6**). The first surface **24** has power reflectivity of 20% (the amplitude reflectivity r=0.45) and the second surface **22** has power reflectivity near 100%. The light from the input fiber **11** has all the wavelengths (λ=1, 2, 3, 4, etc.). After lens **13**, they are collimated. The beam splitter reflects about 50% of light to the bop mirror **19** and transmits the rest of light to the cavity **20**. The phase of light reflected from mirror **19** is proportional to the optical frequency and that of the light reflected from the cavity is a non-linear function of the optical frequency At the bottom arm (output fiber **15**), the frequency dependence of the phase difference between these two beams is shown in FIG. **9**, curve **50**. The light of normalized optical frequencies at an even number produces constructive interference at the bottom channel and that of an odd number produces constructive interference at output fiber **17**. Therefore, the light of wavelength λ=1, 3, 5, etc. will be focused by lens **13** into output fiber **17** and that of wavelength λ=2, 4, 6, etc. will be focused by lens **23** into output fiber **15**. The odd and even channels are thus interleaved to different outputs. This device can also be used as a multiplexer by sending light of even wavelengths through fiber **15** and light of odd wavelengths through fiber **17**. After interference, all the light will come out from fiber **11**.

In FIG. **8C**, a phase retardation plate **21** is placed in the right arm to generate a phase difference between P- and S-polarized light, such that $\psi_{SR}-\psi_{SR'}+\psi_{ret}=\psi_{PR}-\psi_{PR'}$

where Ψret is phase retardation introduced by the phase plate during the round trip.

From now on, it is assumed that the coating on the BS cube and the mirrors have been provided so that $\Psi_{SR}-\Psi_{SR'}=\Psi_{PR}-\Psi_{PR'}=0$.

According to Equation (5), the optical power at the bottom arm is as follows.

$$P_B = \cos^2\left(\frac{\psi_B}{2}\right)$$

The optical power at the left arm is

$$P_L = 1 - P_B = \sin^2\left(\frac{\psi_B}{2}\right)$$

FIG. **9** shows the phase difference, Ψ_B, as a function of normalized frequencies v_c for r=0(dash) and 0.45 (solid). It is seen that when the frequencies are an even integer, the phase difference, Ψ_B, is 2 Π, and when the frequencies are an odd integer, the phase difference is Π. For the curve of r=0.45, shown in plot **50**, the slope of the phase curve is very close to zero when the normalized frequencies are integers. This makes it possible that the phase stays at Π in the neighborhood of odd integers and at 2 Π in the neighborhood of even integers, which is similar to the ideal phase difference between the two interference beams shown in FIG. **5**. FIG. **10** shows the optical power as a function of frequency at the bottom arm for r=0 (dash) and 0.45 (solid). For the case of r=0.45, shown in plot **60**, the shape of transmission curve is fairly close to the ideal case shown in FIG. **4**.

FIGS. **11**, **12** and **13** are the 10log10 (dB) plots of optical power at the bottom arm for r=0.3, 0.4 and 0.5 respectively. It is seen that when the reflectivity is low, the isolation in the blocked band is better. For instance, in FIG. **11**, with r=0.3, the isolation is better than −40 dB. In contrast, in FIG. **13**, with r=0.5, the isolation is −22 dB. The advantage of higher reflectivity is that the transmission curve will fall off steeper.

FIG. **14** shows a Mach-Zehnder type step-phase interferometer where the right arm includes a regular mirror **70** to create a linear phase and the top arm includes a non-linear phase generator **72**.

FIG. **15** shows another type of non-linear phase generator, consisting of three reflection surfaces where the first two surfaces **80** and **82** partially reflect the incident beam **84** (with amplitude reflectivity of r1 and r2) and the third surface **86** has reflectivity close to 100%.

FIG. **16** shows the phase difference between the two interference beams, Ψ_B at one of the output arms for a step-phase interferometer with a three surface non-linear phase generator (such as shown in FIG. **15**), of r1=0.15, r2=0.3. The two sub-cavities have the same optical length and the characteristic frequency is corresponding to the total optical path length of the cavity.

FIG. **17** shows the optical power at one of the output arms for a step-phase interferometer with a three-surface non-linear phase generator (the corresponding phase difference between the two interference beams is shown in FIG. **16**). Notice that the duty cycle of the transmission curve is not 50%. The duty cycle is depending on the values of r1 and r2.

FIG. **18** shows an un-polarized 50/50 beam splitter where the light is to be incident from the left hand side. Side **90** and side **92** are AR-coated, side **94** can be AR or partially reflecting (PR) coated, side **96** is AR or mirror coated, depending on which scheme being used.

FIG. **19**A through **24** shows a variety of step-phase interferometers usable in the present invention.

FIG. **19**A shows an embodiment where the topside **100** of the cube is coated as a mirror to generate a linear phase and the right-hand side **102** of cube is PR coated to be the first surface of a non-linear phase generator. A spacer(s) **104** provides a gap between the cube and a mirror coated surface **106**. Spacer(s) **104** are preferably fabricated of a material having a low coefficient of thermal expansion, such as Zerodur.

FIG. **19**B is similar to **19**A. Instead of making the mirror coating on the top **100** of cube, the mirror coating **103** is located on the second surface of extra piece **101** bonded to the top of cube. There are two advantages for this approach. Firstly, since it is an extra piece, one can control its thickness better. Notice that the error in thickness is related to the error in channel spacing of the communication system. Secondly, since the refraction index and the physical thickness of the mirror substrate changes with temperature, one can use an a thermal material as a substrate such that the temperature does not affect the optical path length (OPL). An a thermal material is a substance that the effect of temperature change on OPD due to the index of refraction is cancelled by the thermal expansion.

FIG. **20** shows an embodiment where the topside **110** of the cube is mirror coated to generate a linear phase, the right-hand side **112** of the cube is AR coated. An optically transmitting piece comprising a first surface **114** having an AR coating and a second surface **116** that has a PR coating is separated from the cube by a first spacer **118**. A piece comprising a first surface with a mirror coating **120** is spaced apart from the second surface **116** with a second spacer(s) **122**. The second surface **116** and the first surface **120** together form the non-linear phase generator in this embodiment.

FIG. **21** is an embodiment where the topside **130** of the cube is AR coated, the right-hand side **132** of the cube is PR coated to be first surface of a non-linear phase generator and the mirror **134** on the topside of cube is an extra piece separated from the cube by spacer(s) **136**. An extra piece having a first surface **138** that is mirror coated is separated from surface **132** by another spacer(s) **140**.

FIG. **22** shows an embodiment where the topside **150** of the cube is mirror coated to be a linear phase generator, the right-hand side **152** of the cube is AR coated and the non-linear phase is achieved by an external three-surface cavity comprising two AR coated surfaces **154**, **156**, two PR coated surfaces **158**,**160** and mirror **162**.

FIG. **23** shows an embodiment where the topside **170** and right-hand side **172** of the cube are AR coated. The mirror **174** for a linear phase generator is separated from the cube by spacer(s) **176**. Three external pieces form the non-linear phase generator. The first piece is separated from the cube with spacer **178**, and comprises a first AR coated surface **180**, and a second PR coated surface **182**. The second piece is separated from the first piece by spacer **184** and comprises a first AR coated surface **186** and a second PR coated surface **188**. The third piece is separated from the second piece with spacer **190** and comprises a first mirror surface **192**.

FIG. **24** shows an embodiment where the topside **170** and right-hand side **172** of the cube are AR coated. The top mirror for a linear phase generator is separated from the cube by spacer(s) **200**. The single external piece **202** that forms the non-linear phase generator is attached to the cube by spacers **204**. The first surface **206** is PR coated and the second surface **208** is mirror coated.

The foregoing description of the invention has been presented for purposes of illustration and description and is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. The embodiments were chosen and described to best explain the principles of the invention and its practical application to thereby enable others skilled in the art to best use the invention in various embodiments and with various modifications suited to the particular use contemplated. The scope of the invention is to be defined by the following claims.

I claim:

1. An optical step-phase interferometer, comprising:

a beamsplitter to separate an incident beam of light into a first beam of light and a second beam of light;

a reflector operatively positioned to reflect said first beam of light to produce a first reflected beam; and

a non-linear phase generator (NLPG) operatively positioned to reflect said second beam of light to produce a second reflected beam, wherein said first reflected beam and said second reflected beam interfere with one another, wherein the frequency dependence of the phase difference between said first reflected beam and said second reflected beam has a step-like function.

2. The optical step-phase interferometer of claim **1**, wherein the step of said phase difference is approximately Π.

3. The optical step-phase interferometer of claim **1**, wherein said first reflected beam and said second reflected beam are combined into two interference beams at said beam splitter, wherein a first interference beam of said two interference beams carries a first subset of signals and a second interference beam of said two interference beams carries a second subset of signals, wherein said first subset of signals is directed to a first port and said second subset of signals is directed to a second port.

4. The optical step-phase interferometer of claim **1**, wherein said reflector comprises a first surface reflector.

5. The optical step-phase interferometer of claim **1**, wherein said reflector comprises a back surface reflector.

6. The optical step-phase interferometer of claim **1**, wherein said NLPG comprises a first reflective surface and a second reflective surface that are separated.

7. The optical step-phase interferometer of claim **6**, wherein said first reflective surface and said second reflective surface are separated by a cavity.

8. The optical step-phase interferometer of claim **7**, wherein said cavity comprises an air-gap.

9. The optical step-phase interferometer of claim **6**, wherein said first reflective surface comprises a partially reflective coating having a reflectivity that is less than one.

10. The optical step-phase interferometer of claim **6**, wherein said second reflective surface comprises nearly 100% reflectivity.

11. The optical step-phase interferometer of claim **7**, wherein said cavity comprises optically transparence material.

12. The optical step-phase interferometer of claim **11**, wherein said first reflective surface comprises a partially reflective coating having a reflectivity that is less than one.

13. The optical step-phase interferometer of claim **12**, wherein said second reflective surface comprises nearly 100% reflectivity.

14. The optical step-phase interferometer of claim **1**, wherein said beamsplitter comprises an unpolarized beamsplitter.

15. The optical step-phase interferometer of claim **14**, wherein said unpolarized beamsplitter comprises an internal beam-splitting coating such that $\Psi_{SR}-\Psi_{SR'}=\Psi_{PR}-\Psi_{PR'}$.

16. The optical step-phase interferometer of claim **14**, wherein said unpolarized beamsplitter comprises an internal beam-splitting coating that affects the phase of said first beam and said second beam such that $(\Psi_{SR}-\Psi_{SR'})-(\Psi_{PR}-\Psi_{PR'})$ is minimized.

17. The optical step-phase interferometer of claim **14**, wherein said unpolarized beamsplitter comprises an internal beam-splitting coating that affects the phase of said first beam and said second beam such that $(\Psi_{SR}-\Psi_{SR'})-(\Psi_{PR}-\Psi_{PR'})$ is approximately zero.

18. The optical step-phase interferometer of claim **14**, wherein said unpolarized beamsplitter comprises a symmetrical internal beam-splitting coating.

19. The optical step-phase interferometer of claim **14**, further comprising a wave plate operatively placed in said first beam or said second beam to compensate the polarization dependent phase difference from said unpolarized beam splitter.

20. The optical step-phase interferometer of claim **1**, wherein the optical path of said first beam is less than that of said second beam.

21. The optical step-phase interferometer of claim **1**, wherein said NLPG comprises a cavity having an optical path length, wherein the optical path length difference (OPLD) between said first beam and said second beam is approximately half of the optical path length of said cavity.

22. The optical step-phase interferometer of claim **1**, further comprising a second beamsplitter positioned to combine said first beam and said second beam to interfere with each other, wherein said optical step-phase interferometer is configured as an optical interleaving Mach-Zehnder type step-phase interferometer.

23. The optical step-phase interferometer of claim **1**, wherein said NLPG comprises a plurality of partially reflecting surfaces and a reflective surface comprising nearly 100% reflectivity.

24. The optical step-phase interferometer of claim **1**, further comprising an input fiber optic to provide said incident beam.

25. The optical step-phase interferometer of claim **3**, further comprising a first output fiber optic and a second output fiber optic, wherein said first output fiber optic is positioned at said first port to collect said first subset and wherein said second fiber optic is positioned at said second port to collect said second subset.

26. The optical step-phase interferometer of claim **1**, further comprising at least one fiber optic positioned to collect a beam comprising the interference of said first reflected beam and second reflected beam.

27. The optical step-phase interferometer of claim **3**, further comprising a circulator to redirect said the first subset of optical signal into a first port.

28. The optical step-phase interferometer of claim **1**, wherein said reflector comprises material that is a thermal.

29. The optical step-phase interferometer of claim **14**, wherein said reflector is a surface of said unpolarized beamsplitter, wherein said unpolarized beamsplitter comprises a partially reflecting surface of said NLPG, wherein said optical step-phase interferometer further comprises at least one spacer to provide at least one cavity between said partially reflecting surface and a mirror coated surface.

30. The optical step-phase interferometer of claim **29**, wherein said at least one spacer comprises a material having a low coefficient of thermal expansion.

31. The optical step-phase interferometer of claim **14**, wherein said reflector comprises a separate piece of material that is fixedly attached to a surface of said unpolarized beamsplitter, wherein said unpolarized beamsplitter comprises a partially reflecting surface of said NLPG, wherein said optical step-phase interferometer further comprises a spacer to provide a cavity between said partially reflecting surface and a mirror coated surface of said NLPG.

32. The optical step-phase interferometer of claim **31**, wherein a spacer is used to fixedly attached said reflector to said surface of said unpolarized beamsplitter.

33. The optical step-phase interferometer of claim **32**, wherein a reflector coating is on the back side of said separated piece of material.

34. An optical step-phase interferometer, comprising:

a first input fiber for providing a first set of wavelengths;

a second input fiber optic for providing a second set of wavelengths;

a reflector operatively positioned to reflect said first set of wavelengths to produce a first reflected beam;

a non-linear phase generator (NLPG) operatively positioned to reflect said second set of wavelengths to produce a second reflected beam; and

a beamsplitter to combine said first reflected beam and said second reflected beam into a third fiber optic.

35. A method of interleaving frequencies of light, comprising:

separating an incident beam of light into a first beam of light and a second beam of light;

reflecting said first beam of light to produce a first reflected beam; and

reflecting said second beam of light with a non-linear phase generator (NLPG) to produce a second reflected beam, wherein said first reflected beam and said second reflected beam interfere with one another, wherein the frequency dependence of the phase difference between said first reflected beam and said second reflected beam has a step-like function.

36. The method of claim **35**, wherein the step of said phase difference is approximately Π.

37. The method of claim **35**, wherein said first reflected beam and said second reflected beam are combined into two interference beams at said beam splitter, wherein a first interference beam of said two interference beams carries a first subset of signals and a second interference beam of said two interference beams carries a second subset of signals, wherein said first subset of signals is directed to a first port and said second subset of signals is directed to a second port.

38. The method of claim **35**, wherein the step of separating an incident beam is carried out with an unpolarized beamsplitter, the method further comprising compensating for any polarization dependent phase difference generated by said unpolarized beam splitter.

39. The method of claim **38**, wherein the step of compensating for any polarization dependent phase difference is carried out with an internal coating within said unpolarized beamsplitter, wherein said internal coating affects the phase of said first beam and said second beam such that $(\Psi_{SR}-\Psi_{RS'})-(\Psi_{PR}-\Psi_{PR'})$ is minimized.

40. The method of claim **38**, wherein the step of compensating for any polarization dependent phase difference is carried out with a wave plate operatively placed in said first beam or said second beam.

41. The method of claim **35**, where the optical path of said first reflected beam is less than that of said second reflected beam.

42. The method of claim **35**, wherein said NLPG comprises a cavity having a cavity length, wherein the optical path length difference (OPLD) between said first beam and said second beam is approximately half of said the optical path length of the cavity.

43. The method of claim **35**, further comprising a second beamsplitter positioned to combine said first beam and said second beam, wherein said first reflected beam and said second reflected beam interfere with one another, wherein said optical step-phase interferometer is configured as an optical interleaving Mach-Zehnder type interferometer.

44. The method of claim **35**, further comprising providing said incident beam from an input fiber optic.

45. The method of claim **35**, further comprising positioning at least one fiber optic to collect the interference beam of said first reflected beam with said second reflected beam.

46. The method of claim **37**, wherein an interference beam is produce when said first reflected beam and said second reflected beam interfere with one another, the method further comprising positioning a circulator to collect said interference beam.

* * * * *

EXHIBIT B

US007522343B2

(12) United States Patent
Hsieh

(10) **Patent No.: US 7,522,343 B2**
(45) **Date of Patent: Apr. 21, 2009**

(54) **MICHELSON INTERFEROMETER BASED DELAY LINE INTERFEROMETERS**

(75) Inventor: **Yung-Chieh Hsieh**, San Jose, CA (US)

(73) Assignee: **Optoplex Corporation**, Fremont, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **11/485,653**

(22) Filed: **Jul. 11, 2006**

(65) **Prior Publication Data**

US 2007/0070505 A1 Mar. 29, 2007

Related U.S. Application Data

(63) Continuation-in-part of application No. 11/360,959, filed on Feb. 22, 2006, and a continuation-in-part of application No. 10/796,512, filed on Mar. 8, 2004, now Pat. No. 7,145,727.

(60) Provisional application No. 60/698,584, filed on Jul. 11, 2005, provisional application No. 60/748,096, filed on Dec. 5, 2005, provisional application No. 60/786,630, filed on Mar. 27, 2006, provisional application No. 60/655,548, filed on Feb. 23, 2005, provisional application No. 60/689,867, filed on Jun. 10, 2005.

(51) **Int. Cl.**
G02B 27/14 (2006.01)

(52) **U.S. Cl.** **359/634**; 359/629

(58) **Field of Classification Search** 359/627–634, 359/578; 398/159, 141, 158, 208; 356/477; 250/339.02

See application file for complete search history.

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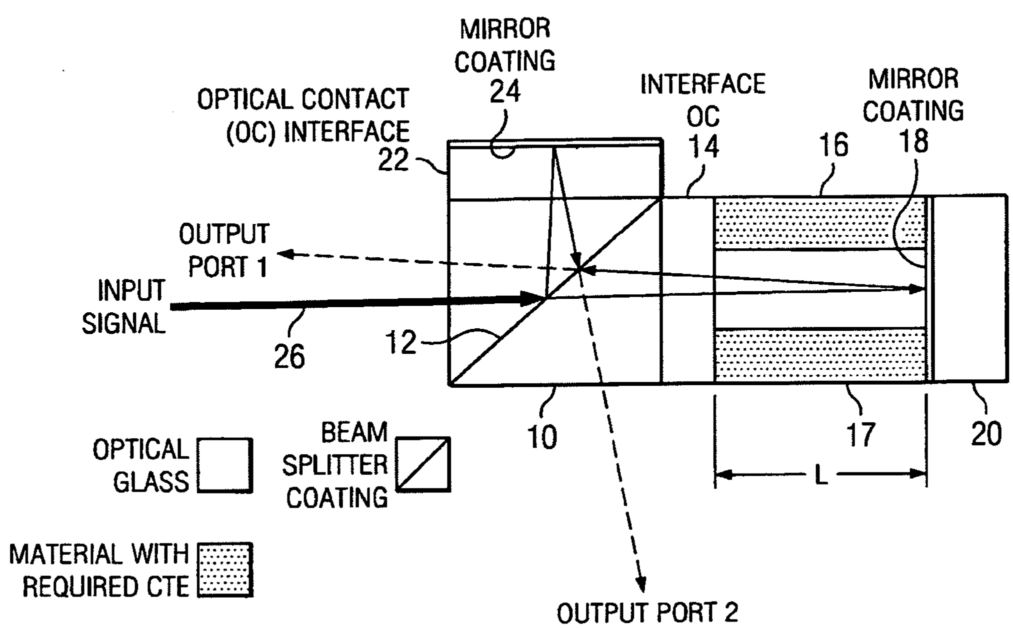
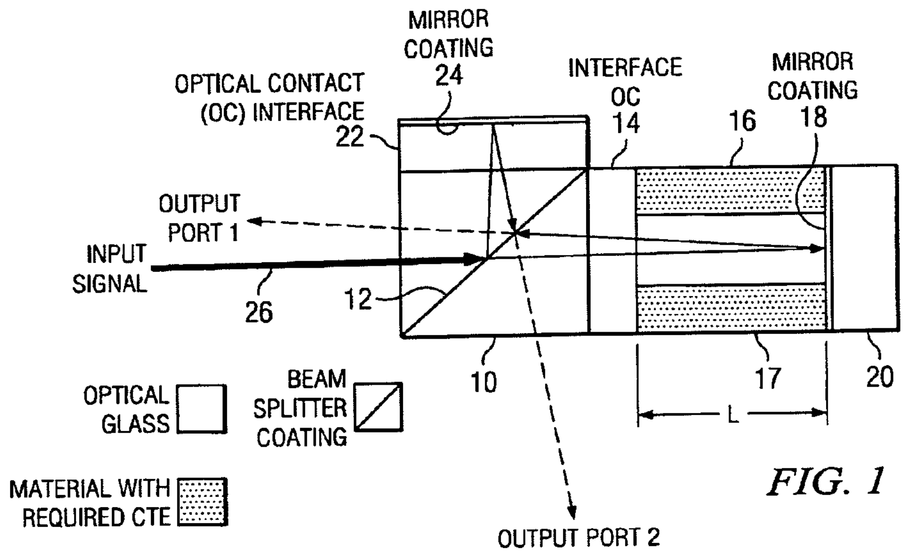
Primary Examiner—Mohammed Hasan
(74) *Attorney, Agent, or Firm*—John P. Wooldridge; Antonio R. Durando

(57) **ABSTRACT**

An interferometer includes a means for splitting, at a splitting location, an input light beam into a first beam and a second beam; and means for recombining, at a recombination location, the first beam and the second beam. The interferometer is designed such that the first beam will travel a first optical path length (OPL) from the splitting location to the recombination location, and the second beam will travel a second OPL from the splitting location to the recombination location and such that when the input light beam has been modulated at a data rate comprising a time interval, then the difference in optical path lengths between the first OPL and the second OPL is about equal to the time interval multiplied by the speed of light.

13 Claims, 6 Drawing Sheets

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OPTICAL CONTACT
(OC) INTERFACE
22
INTERFACE
OC
14
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MIRROR
COATING
18
OUTPUT
PORT 1
INPUT
SIGNAL
26
12
10
17
20
L
OPTICAL
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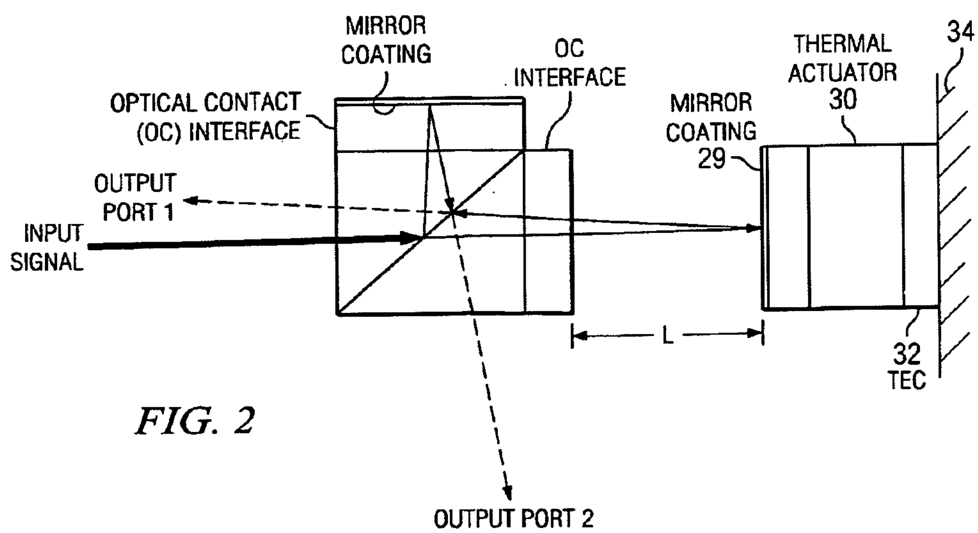
BEAM
SPLITTER
COATING
MATERIAL WITH
REQUIRED CTE
OUTPUT PORT 2

FIG. 1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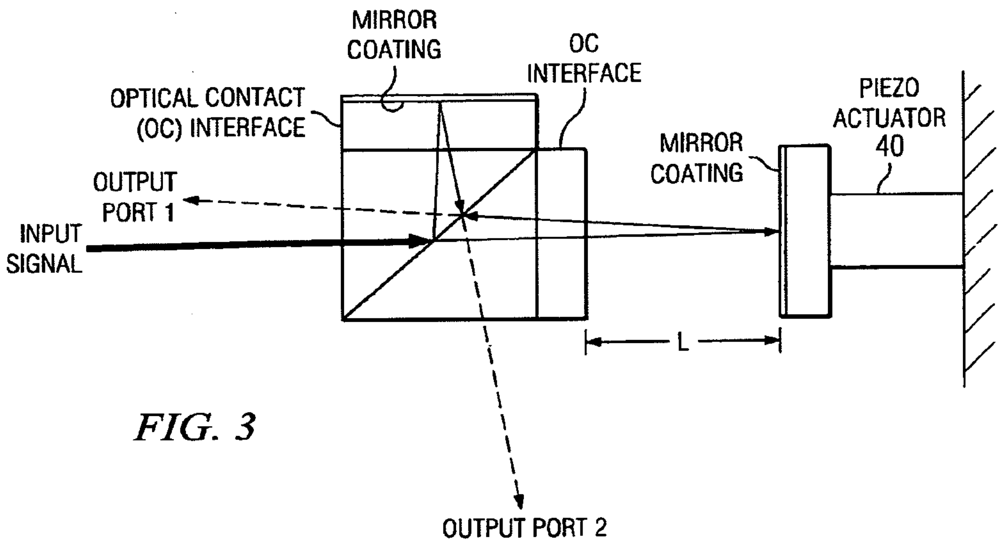
OUTPUT
PORT 1
INPUT
SIGNAL
L
32
TEC
OUTPUT PORT 2

FIG. 2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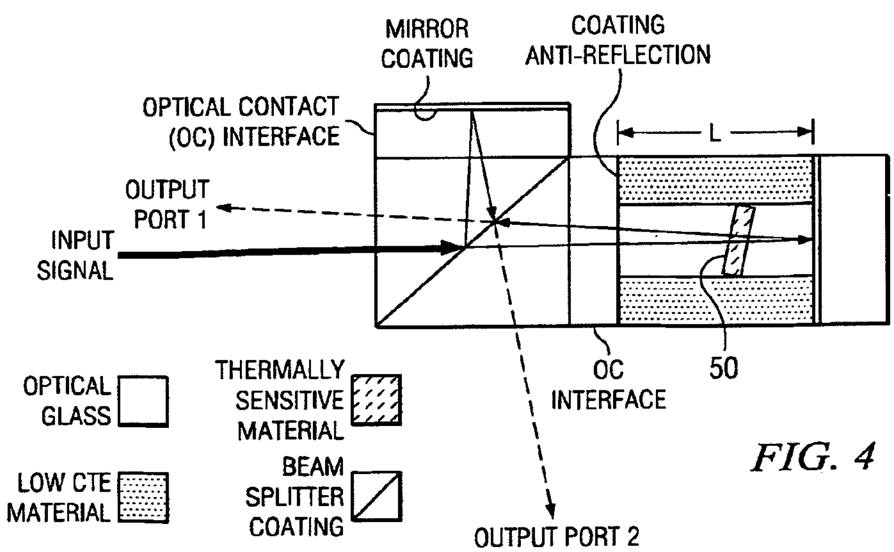
INPUT
SIGNAL
L
OUTPUT PORT 2

FIG. 3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COATING
ANTI-REFLECTION
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PORT 1
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SIGNAL
OC
INTERFACE
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GLASS
THERMALLY
SENSITIVE
MATERIAL
LOW CTE
MATERIAL
BEAM
SPLITTER
COATING
OUTPUT PORT 2

FIG. 4

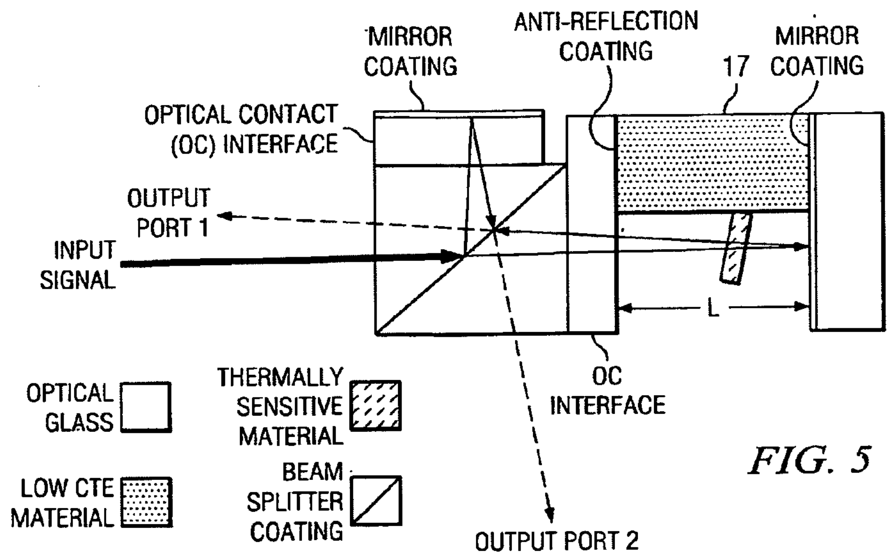

FIG. 5

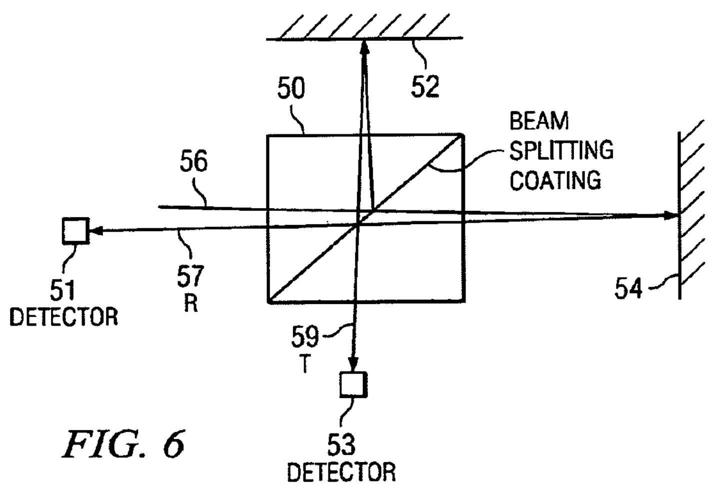

FIG. 6

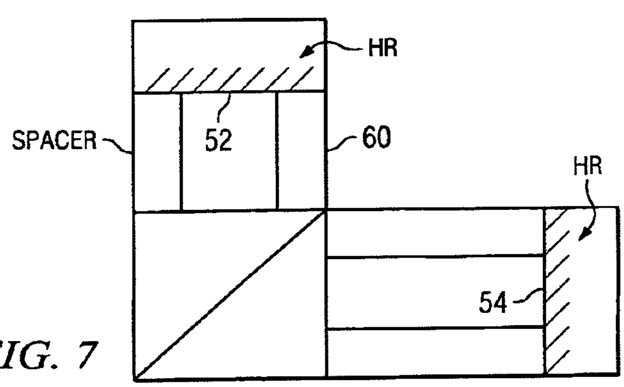

FIG. 7

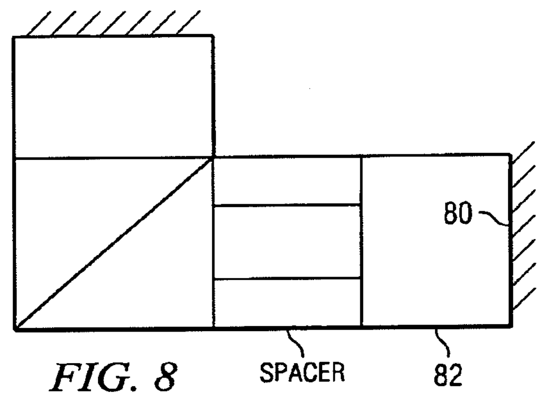

FIG. 8

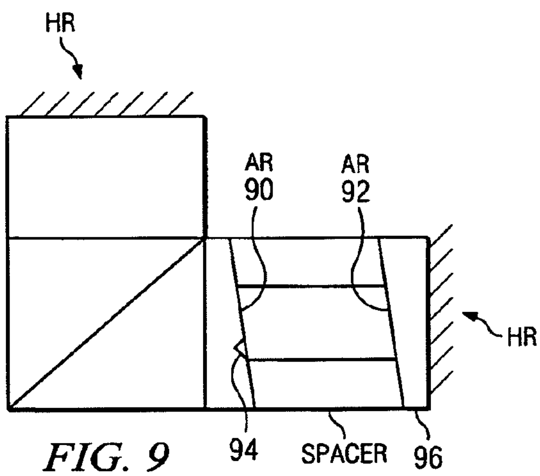

FIG. 9

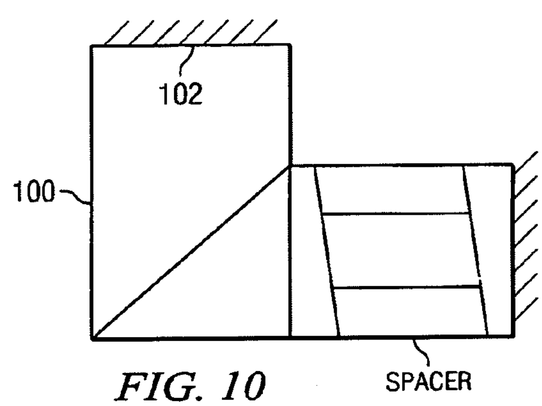

FIG. 10

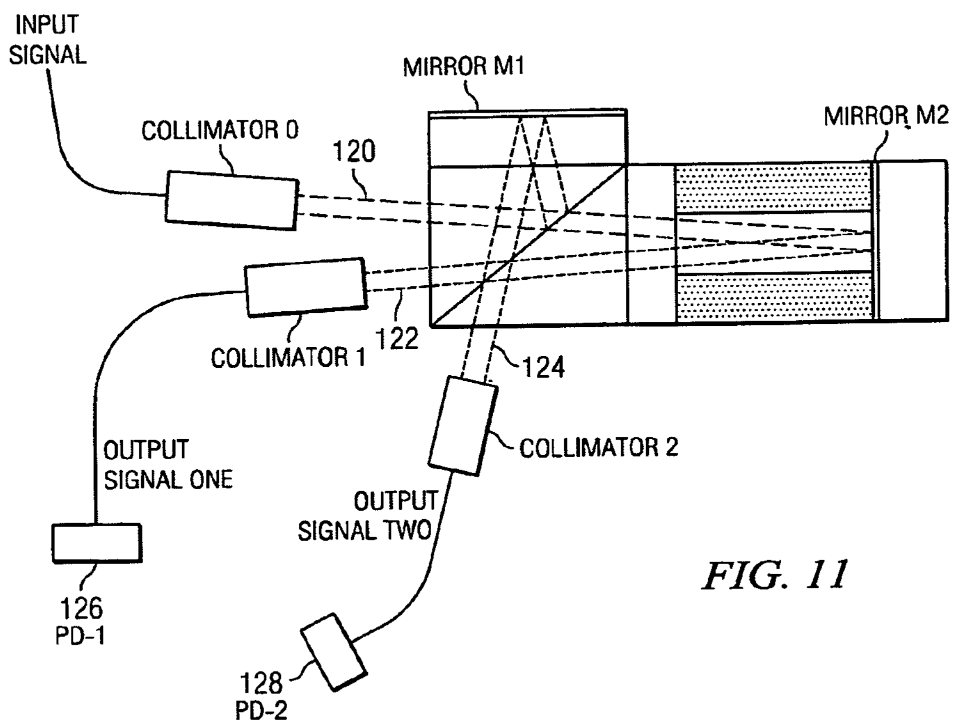
INPUT SIGNAL
MIRROR M1
COLLIMATOR 0
120
MIRROR M2
COLLIMATOR 1
122
124
COLLIMATOR 2
OUTPUT SIGNAL ONE
OUTPUT SIGNAL TWO
126
PD-1
128
PD-2

FIG. 11

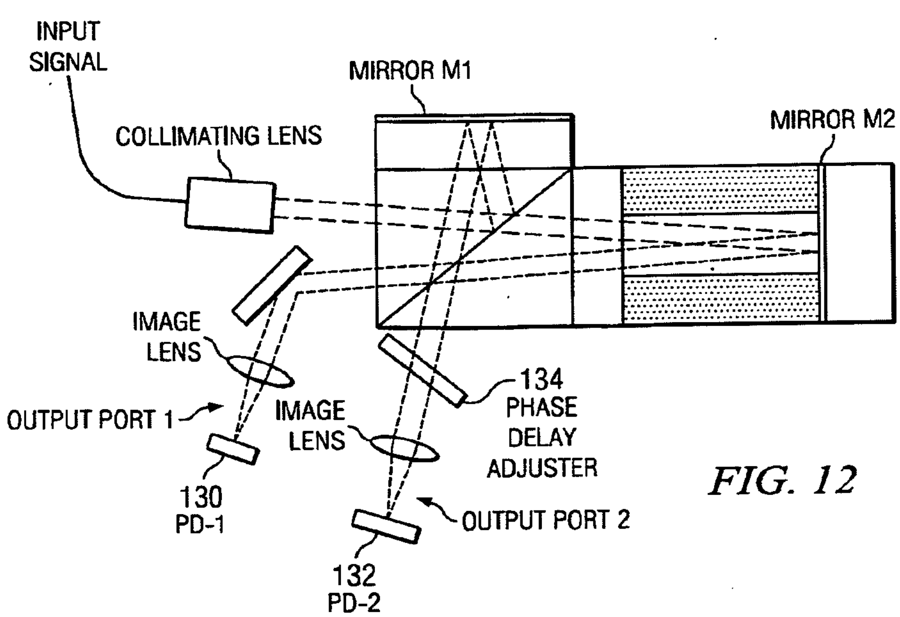
INPUT SIGNAL
MIRROR M1
COLLIMATING LENS
MIRROR M2
IMAGE LENS
134
PHASE DELAY ADJUSTER
OUTPUT PORT 1
IMAGE LENS
130
PD-1
OUTPUT PORT 2
132
PD-2

FIG. 12

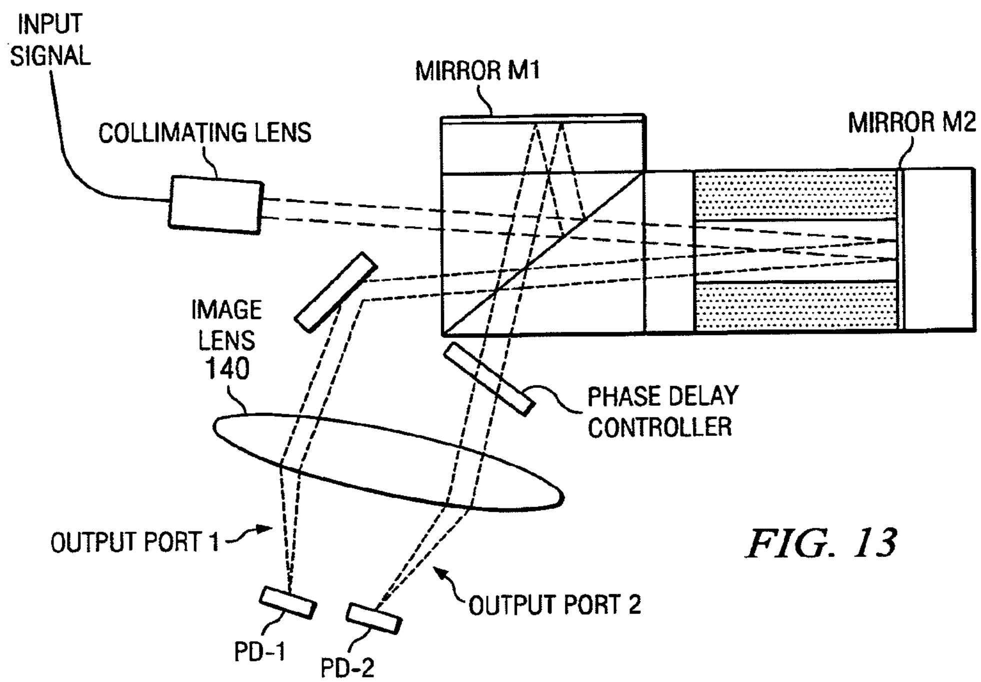
INPUT SIGNAL
MIRROR M1
COLLIMATING LENS
MIRROR M2
IMAGE LENS 140
PHASE DELAY CONTROLLER
OUTPUT PORT 1
OUTPUT PORT 2
PD-1
PD-2

FIG. 13

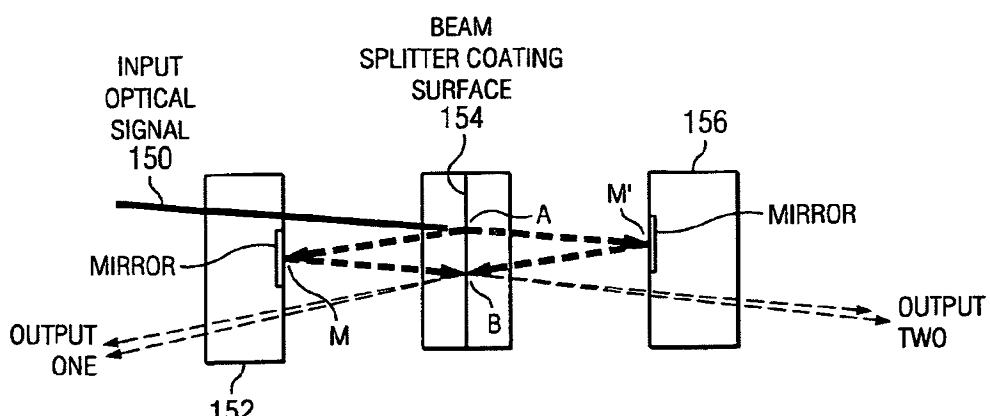
BEAM SPLITTER COATING SURFACE 154
INPUT OPTICAL SIGNAL 150
156
M'
A
MIRROR
MIRROR
M
B
OUTPUT ONE
OUTPUT TWO
152

FIG. 14

MICHELSON INTERFEROMETER BASED DELAY LINE INTERFEROMETERS

This application also claims priority to U.S. Provisional Patent Application Ser. No. 60/698,584, filed Jul. 11, 2005, titled: "Integration of Michelson Differential Phase Shift Keying (DPSK) Demodulator with Photo Detector," incorporated herein by reference. This application also claims priority to U.S. Provisional Patent Application Ser. No. 60/748,096, filed Dec. 5, 2005, titled: "Co-package DQPSK Demodulator by Michelson Interferometer," incorporated herein by reference. This application also claims priority to U.S. Provisional Patent Application Ser. No. 60/786,630, filed Mar. 27, 2006, titled: "Free-Space Optical Hybrid," incorporated herein by reference. This is a continuation-in-part of U.S. patent application Ser. No. 10/796,512, filed Mar. 8, 2004, now U.S. Pat. No. 7,147,727 titled: "Unpolarized Beam Splitter Having Polarization-Independent Phase Difference When Used As An Interferometer," incorporated herein by reference. This is a continuation-in-part of U.S. patent application Ser. No. 11/360,959, filed Feb. 22, 2006, titled "Michelson Interferometer Based Delay Line Interferometers," incorporated herein by reference. This application claims priority to U.S. Provisional Patent Application Ser. No. 60/655,548, filed Feb. 23, 2005, titled: "Athermal Optical Decoder For DPSK," incorporated herein by reference. This application also claims priority to U.S. Provisional Patent Application Ser. No. 60/689,867, filed Jun. 10, 2005, titled: "DPSK by Michelson interferometer," incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to differential phase-shift keying (DPSK) in telecommunication, and more specifically, it relates to methods in DPSK for converting a phase-keyed signal to an intensity-keyed signal.

2. Description of Related Art

Phase-shift keying (PSK) is a digital modulation scheme that conveys data by changing, or modulating, the phase of a reference signal (the carrier wave). Any digital modulation scheme uses a finite number of distinct signals to represent digital data. In the case of PSK, a finite number of phases are used. Each of these phases is assigned a unique pattern of binary bits. Usually, each phase encodes an equal number of bits. Each pattern of bits forms the symbol that is represented by the particular phase. The demodulator, which is designed specifically for the symbol-set used by the modulator, determines the phase of the received signal and maps it back to the symbol it represents, thus recovering the original data. This requires the receiver to be able to compare the phase of the received signal to a reference signal—such a system is termed coherent.

Alternatively, instead of using the bit patterns to set the phase of the wave, it can instead be used to change it by a specified amount The demodulator then determines the changes in the phase of the received signal rather than the phase itself. Since this scheme depends on the difference between successive phases, it is termed differential phase-shift keying (DPSK). DPSK can be significantly simpler to implement than ordinary PSK since there is no need for the demodulator to have a copy of the reference signal to determine the exact phase of the received signal (it is a non-coherent scheme).

In telecommunication technology, differential phase-shift keying (DPSK) requires a decoding method in order to convert the phase-keyed signal to an intensity-keyed signal at the receiving end. The decoding method can be achieved by comparing the phase of two sequential bits. In principle, it splits the input signal beam into two channels with a small delay before recombining them. After the recombination, the beams from the two channels interfere constructively or destructively. The interference intensity is measured and becomes the intensity-keyed signal. To achieve this, one channel has an optical path longer than the other one by a distance equivalent to the photon flight time of one bit. For instance, in a 40 Gbit per second system, one bit is equal to 25 ps, and light travels 7.5 mm in that period. In this example, the optical path difference (OPD) between the two channels is 7.5 mm.

The Mach-Zehnder type interferometer with a desired OPD between the two channels is currently used for decoding purposes. Because of the properties of optical interference, a change in OPD can greatly affect interference intensity. Moreover, the optical path in each arm is much longer than its difference. Therefore, a sophisticated temperature control is required to maintain the optical path in each arm in order to assure that the change in the OPD is much less than a small fraction of one wavelength, e.g., ~10 nm. This is difficult and expensive, especially for an interferometer with a long optical path.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a DPSK demodulator that determines the changes in the phase of a received signal (i.e., the difference between successive phases).

It is another object to use various disclosed embodiments of novel Michelson type interferometers as DPSK demodulators to determine the changes in the phase of a received signal.

These and other objects will be apparent based on the disclosure herein.

The invention is various embodiments of novel Michelson type interferometers used as DPSK demodulators to determine the changes in the phase of a received signal. In the demodulator, the input beam is split into two portions at the beam splitter. The two beams travel a different path and are returned by their corresponding reflector. Because the OPL's are different, the two returned beams have a time delay with respect to each other. The difference between the two OPL's is designed to assure that the delay is approximately equal to the time delay of any two successive bits or data symbols.

A general embodiment of the invention is a Michelson type interferometer that includes a means for splitting, at a splitting location, an input light beam into a first beam and a second beam; and means for recombining, at a recombination location, the first beam and the second beam. The interferometer is designed such that the first beam will travel a first optical path length (OPL) from the splitting location to the recombination location, and the second beam will travel a second OPL from the splitting location to the recombination location and such that when the input light beam has been modulated at a data rate comprising a time interval, then the difference in optical path lengths between the first OPL and the second OPL is about equal to the time interval multiplied by the speed of light.

In specific embodiments of the interferometer, the means for recombining can comprise a first reflector positioned to reflect the first beam, and the means for recombining can further comprise a second reflector positioned to reflect the second beam. In this embodiment, one of the reflectors is separated from the splitting location by a distance sufficient to make the difference in optical path lengths between the first OPL and the second OPL to be about equal to the time interval multiplied by the speed of light The separation of the reflector can be accomplished with at least one spacer that can have either a low or a high coefficient of thermal expansion (CTE). In another embodiment, the separated reflector is fixedly attached to means for adjusting the distance.

The invention also contemplates methods of using the different embodiments of interferometers described herein. A general embodiment of the method includes the steps of providing an input light beam modulated at a data rate comprising a time interval; splitting, at a splitting location, said input light beam into a first beam and a second beam; and recombining, at a recombination location, said first beam and said second beam, wherein said first beam travels a first optical path length (OPL) from said splitting location to said recombination location, wherein said second beam travels a second OPL from said splitting location to said recombination location, wherein the difference in optical path lengths between said first OPL and said second OPL is about equal to said time interval multiplied by the speed of light.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated into and form a part of the disclosure, illustrate embodiments of the invention and, together with the description, serve to explain the principles of the invention.

FIG. **1** illustrates a Michelson-based delay line interferometer.

FIG. **2** shows a high speed thermally tuned DLI.

FIG. **3** shows a piezo tuned tunable DLI.

FIG. **4** shows a Michelson-based delay line interferometer that includes a thermally tuned phase modulator inserted in the optical path.

FIG. **5** shows a single-spacer Michelson-based delay line interferometer.

FIG. **6** shows a prior art Michelson interferometer, with two detectors located at a specific distance.

FIG. **7** illustrates the use of a zero thermal expansion material as a spacer to minimize the change in OPD.

FIG. **8** shows a Michelson-based delay line interferometer with a second surface mirror in both paths.

FIG. **9** shows a Michelson-based delay line interferometer with a second surface mirror in both paths and antireflection coatings on wedged optical elements in one arm.

FIG. **10** shows a beamsplitter with an extended upper arm.

FIG. **11** shows a Michelson DLI with two output ports fiber coupled to photodetectors.

FIG. **12** shows a Michelson DLI with outputs directly coupled to photo detectors.

FIG. **13** shows a Michelson DLI that uses a single lens to directly couple the DLI outputs to photo detectors.

FIG. **14** shows another embodiment utilizing near normal incidence.

DETAILED DESCRIPTION OF THE INVENTION

An embodiment of the present invention is illustrated in FIG. **1**, which shows a Michelson-based delay line interferometer (DLI) formed by a beamsplitter **10** with beamsplitting coating **12** An optical glass element **14** is affixed to the right hand side of the beamsplitter. Element **14** can be affixed, e.g., with an index matching adhesive as known in the art. Spacers **16** and **17**, having a length L, and made of a material having a low coefficient of thermal expansion (CTE), are affixed to the right hand side of the optical element **14**. To the right hand side of the spacers is a mirror coating **18** on a substrate **20**. A second optical glass element **22** is affixed to the top of beamsplitter **10**. A mirror (reflective) coating **24** is located on the second surface of element **22**. When elements **14** and **22** are of the same material and thickness, the round-trip optical path length difference (OPD) between mirror coating **18** and mirror coating **24** is 2 times L, where L is the length of the spacer **16**. The input signal **26** is impingent on the left-hand side of the beamsplitter. Beamsplitting coating **12** splits the light into two beams and each beam carries about 50% of the total power. After each beam is reflected by its corresponding mirror, it hits the beamsplitter in its respective return path, and therefore two beams are split into 4 beams. Interference occurs in both the leftward and the downward beams to form the two output beams of the DLI. The relationship between the free-spectral-range (FSR) and OPD is:

$$FSR = \frac{C}{(OPD)},$$

where C is the speed of light. To make the DLI spectrum to not change with temperature, the CTE of the material that is used for the spacer(s) has to be extremely small. Materials like Zerodur or ULE, e.g., can be used. Both materials have a CTE that is about 0.05 ppm.

A second embodiment that can be understood with reference to FIG. **1** is a thermally tunable DLI. To make the spectrum of the DLI tunable, the material used for the spacers **16** and **17** should have an appropriately high CTE such that when the temperature changes, the OPD will increase or decrease. It turns out that the spectrum of the DLI shifts accordingly. The temperature of the DLI can be adjusted with a thermal electric cooler (TEC) or with a heater.

FIG. **2** shows another type of thermally tuned DLI. In this case, a mirror substrate **28** (between the mirror coating **29** and the actuator) with a mirror coating **29** is mounted on a thermal actuator **30**. The thermal actuator is a material with an appropriate CTE. The TEC **32** is used to provide the heat to or remove the heat from the actuator to adjust the temperature. As shown in FIG. **2**, the left hand side of the TEC is connected to the actuator and its right hand side contacts to a heat sink **34**. When the temperature of the actuator increases, the thermal expansion moves the mirror to the left hand side. For a given temperature change, to maximize the movement, the CTE of the actuator has to be large. Moreover, the response time of this device is determined by how long the heat takes to propagate across the actuator. Therefore, to minimize the response time, a material of high thermal conductivity, e.g., Aluminum or Copper is recommended. One can use Aluminum Nitride with a mirror coating on it to replace the combinational function of the mirror substrate **28** and the actuator **30**, because it has high thermal conductivity, low CTE and excellent surface quality.

The DLI of FIG. **2** has much higher tuning speed and low power consumption than the tunable embodiment of FIG. **1** in which the whole piece of glass must be heated or cooled to tune the spectrum.

FIG. **3** shows a Piezo tuned DLI. The right mirror is mounted to a Piezo actuator **40**. When a voltage is applied across the actuator, the length of the actuator varies according to the magnitude of applied voltage. The frequency response of the device can be easily higher than one KHz. The advantage of this approach is in its high speed and low power consumption.

FIG. **4** shows a DLI whose structure is similar to the device shown in FIG. **1**. In this case, there is a thermally tuned phase modulator **50** inserted in the optical path and the temperature of the phase modulator can be adjusted by a TEC or by heat, which is not shown in the diagram. Spacers of this device are low CTE material. The only thermally sensitive part is the phase modulation window inserted in the optical path. The window material should be optically transparent and the g-factor is a function of temperature.

Assuming that the index and thickness of the phase modulator are n and L_0 respectively, the single trip optical path length is

$$OPL = L + (n-1)L_0.$$

When the temperature changes, the OPL variation is:

$$\frac{d[OPL]}{dT} = \frac{dL}{dT} + (n-1)\frac{dL_0}{dT} + L_0\frac{dn}{dT}$$
$$= 0 + L_0\left[(n-1)\alpha + \frac{dn}{dT}\right]$$
$$= L_0 g$$

where

$$g = \left[(n-1)\alpha + \frac{dn}{dT}\right],$$

where α is the coefficient of thermal expansion of the phase modulator. In the deviation, it has assumed that the spacer material has zero thermal expansion, i.e., dL/dT=0. The g-factor is a material property. For fused silica glass and Silicon, the g-factor is about 10 ppm/deg-C and 200 ppm/deg-C respectively. If the material is silicon, with a thickness of 100 μm, one can change the OPL by 20 nm with one degree of temperature change.

The embodiment of FIG. **4** has lower power consumption and a higher tuning speed than those of the tunable embodiment of FIG. **1**. The TEC/heat is only applied to a thin piece of phase modulation window **50**, rather than the entire spacer. FIG. **5** shows a single-spacer (**17**) Michelson-based delay line interferometer. The phase modulation window can be used to provide tunability when configured as taught in U.S. Pat. No. 6,816,315, which is incorporated herein by reference.

The polarization dependent property of a Michelson DLI is determined by the beam splitter coating. In order to minimize the PDF (polarization dependent frequency shift), the coating on the beam splitter should have minimized polarization dependent phase (PDP). To achieve this, the coating has to be symmetrical. See U.S. Pat. No. 6,587,204, incorporated herein by reference and U.S. patent application Ser. No. 10/796,512, incorporated herein by reference.

It is well known that a Michelson interferometer includes one beamsplitter **50** and two mirrors **52** and **54**, as shown in FIG. **6**. When light **56** is provided from a coherent light source (such as a laser), the interference intensity can be described as

$$I = A + B\cos(4\pi L\upsilon/C),$$

where C is the speed of light, υ is the optical frequency of the light source, A and B are two constants determined by the two mirrors and the beam splitter, and L equals one half of the OPD between the two arms. For a given υ, the interference intensity is a function of L. The challenge is to hold the two mirrors steadily, i.e., to less than a fraction of one wavelength, over a temperature range from −5 to 70 degree C. The two beams reflected by the two mirrors interfere at the beam splitter, constructively or destructively, and form two output beams, **57** and **59** in FIG. **6**. The interference intensities of these two output beams are complementary. One should also note that the time of flight from the beamsplitter coating to the corresponding detectors (**51** and **53**) is important The time difference between them should be much less than the duration of one bit For use in DQPSK embodiments, the invention is designed to identify phase changes of 0, 90, 180 and 270 degrees.

In order to reduce the thermal and dispersion issue that might be caused by the glass material, two arms should have the same length of glass, and hence their OPD comes mainly from the difference of the air path. This OPD is equal to a distance that is equivalent to the needed time delay. In a hermetically sealed condition, the length of the air path is affected by the spacer used. (Tunability can be provided by providing a gas within the hermetically sealed chamber and providing a mechanism, e.g., a vacuum/pressure pump to change the pressure within the chamber.) As shown in FIG. **7**, the use of a zero thermal expansion material, such as Zerodur or ULE, as the spacer **60**, the change in OPD can be minimized or reduced. Because the two beams experience the same glass path length, with the aid of the zero expansion spacer this design is athermal. Many variations can be derived from this design. For instance, by removing the pair of spacers from one arm, one can achieve the same functionality. This design has been discussed above with reference to FIG. **1**. FIG. **8** shows an embodiment similar to FIG. **1** except that the mirror **80** in the right arm is located on the back surface of optical element **82** FIG. **9** is similar to FIG. **8** except that it includes antireflection coatings **90** and **92** on wedged optical elements **94** and **96**, respectively. The wedges and AR coatings prevent reflections from those surfaces. In FIG. **9**, the right arm has wedged optical elements with antireflection coatings on them. Note that the upper arm can be constructed with the same antireflection wedges. FIG. **10** provides a beamsplitter **100** with an extended upper arm and a mirror coating **102**. The right arm of this embodiment is identical to that of FIG. **9**.

BACKGROUND

FIG. **11** shows a Michelson DLI that is a 3 port device having one input **120** and two outputs **122** and **124**. Typically, all three ports are fiber coupled. The light of the two output ports are each connected to a photo detector (**126**, **128**), which converts the optical signals into electronic signals.

FIG. **12** shows an embodiment of the present invention that integrates the DPSK demodulator with a pair of photo detectors. In other words, instead of coupling the two output signals into fibers, the two output light signals are sent to the photo-detectors (**130**, **132**) directly. Since the optical path lengths from the input port to the two output ports have to be almost identical, in one of the optical paths there is a phase delay adjuster **134**. To adjust the optical path length, one can vary the thickness of the flat or the incident angle to the plate. This approach is advantageous because the size and cost of the receiver can be reduced significantly. Further, the coupling loss to the detector is smaller than to the fiber, thereby reducing the insertion loss of the receiver.

FIG. **13** shows a design that is similar to that of FIG. **12**, but with two detectors that share one lens **140**. This configuration allows the two detectors to be very close to each other.

FIG. **14** shows another embodiment utilizing near normal incidence. The optical path length difference of AMB and AM'B is equal to speed of light multiplied by the time duration of two adjacent bits. In the figure, input beam **150** passes through optical flat **152**, and is split at point A of beam splitter coating **154**. One of the split beams is then reflected from mirror coating M on optical flat **152**, and the other beam is reflected from M', which is a coating on a second optical flat **156**. The beams are recombined at point B of beam splitter coating **154** to form two output channels **158** and **160**. In this case, each output channel includes two beams. The optical path difference between the two spit beams can be changed by changing the distance from coating M to beam splitter coating **154** relative to the distance from coating M' to beam splitter coating **154**. Alternate methods for varying the phase of the two split beams can be used, e.g., a phase adjusting optic such as used in FIG. **12** can be inserted in one of the split beams. Other methods will be apparent to those skilled in the art based on this disclosure.

The foregoing description of the invention has been presented for purposes of illustration and description and is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. For example, for use in QDPSK embodiments, the invention can be designed to identify phase changes of 0, 90, 180 and 270 degrees. The embodiments disclosed were meant only to explain the principles of the invention and its practical application to thereby enable others skilled in the art to best use the invention in various embodiments and with various modifications suited to the particular use contemplated. The scope of the invention is to be defined by the following claims.

I claim:

1. An interferometer, comprising:

means for splitting, at a splitting location, an input light beam into a first beam and a second beam;

means for recombining, at a recombination location, said first beam and said second beam to produce at least one output beam, wherein said first beam will travel a first optical path length (OPL) from said splitting location to said recombination location, wherein said second beam will travel a second OPL from said splitting location to said recombination location, wherein when said input light beam carries phase modulated data with a fixed time interval between two adjacent data symbols, then the difference in optical path lengths between said first OPL and said second OPL is about equal to said time interval multiplied by the speed of light;

a photodetector for detecting each said output beam, wherein said at least one output beam is coupled into said photodetector without at least one fiber optic between said recombination location and said photodetector; and

at least one lens operatively positioned between said recombination location and said photodetector.

2. The interferometer of claim **1**, wherein said means for splitting comprises a non-polarizing beamsplitter (NPB).

3. The interferometer of claim **1**, wherein said means for splitting and said means for recombining comprise one beamsplitter.

4. An interferometer, comprising:

means for splitting, at a splitting location, an input light beam into a first beam and a second beam;

means for recombining, at a recombination location, said first beam and said second beam to produce at least one output beam, wherein said first beam will travel a first optical path length (OPL) from said splitting location to said recombination location, wherein said second beam will travel a second OPL from said splitting location to said recombination location, wherein when said input light beam carries phase modulated data with a fixed time interval between two adjacent data symbols, then the difference in optical path lengths between said first OPL and said second OPL is about equal to said time interval multiplied by the speed of light; and

means for detecting each said output beam, wherein said at least one output beam comprises a first output beam and a second output beam, said interferometer further comprises means for adjusting the phase of one of said first output beam or said second output beam.

5. An interferometer, comprising:

means for splitting, at a splitting location, an input light beam into a first beam and a second beam;

means for recombining, at a recombination location, said first beam and said second beam to produce at least one output beam, wherein said first beam will travel a first optical path length (OPL) from said splitting location to said recombination location, wherein said second beam will travel a second OPL from said splitting location to said recombination location, wherein when said input light beam carries phase modulated data with a fixed time interval between two adjacent data symbols, then the difference in optical path lengths between said first OPL and said second OPL is about equal to said time interval multiplied by the speed of light; and

means for detecting each said output beam, wherein said interfereometer comprises a first optic comprising a first portion that is transparent to a wavelength of interest and a second portion that is reflective to said wavelength, a beam splitter with a beam splitter coating and a second optic comprising a third portion that is transparent to said wavelength and a fourth portion that is reflective to said wavelength, wherein said beam splitter coating is utilized as both said means for splitting and said means for recombining.

6. An interferometer, comprising:

means for splitting, at a splitting location, an input light beam into a first beam and a second beam;

means for recombining, at a recombination location, said first beam and said second beam to produce at least one output beam, wherein said first beam will travel a first optical path length (OPL) from said splitting location to said recombination location, wherein said second beam will travel a second OPL from said splitting location to said recombination location, wherein when said input light beam carries phase modulated data with a fixed time interval between two adjacent data symbols, then the difference in optical path lengths between said first OPL and said second OPL is about equal to said time interval multiplied by the speed of light; and

means for detecting each said output beam, wherein said means for recombining comprise a first reflector positioned to reflect said first beam, wherein said means for recombining further comprise a second reflector positioned to reflect said second beam.

7. The interferometer of claim **6**, wherein one of said first reflector and said second reflector is separated from said splitting location by a distance sufficient to make the difference in optical path lengths between said first OPL and said second OPL to be about equal to said time interval multiplied by the speed of light.

8. The interferometer of claim **6**, wherein one of said first reflector and said second reflector is separated with at least one spacer from said splitting location by a distance sufficient to make the difference in optical path lengths between said first OPL and said second OPL to be about equal to said time interval multiplied by the speed of light.

9. The interferometer of claim **8**, wherein said at least one spacer comprises a material having a low coefficient of thermal expansion (CTE).

10. The interferometer of claim **8**, wherein said at least one spacer comprises a material having a high coefficient of thermal expansion.

11. The interferometer of claim **6**, wherein one of said first reflector and said second reflector is a separated reflector that is separated from said splitting location by a distance sufficient to make the difference in optical path lengths between said first OPL and said second OPL to be about equal to said time interval multiplied by the speed of light, wherein said separated reflector is fixedly attached to means for adjusting said distance.

12. The interferometer of claim **6**, further comprising a thermally tunable phase modulator for adjusting the optical path length of said first OPL or said second OPL.

13. The interferometer of claim **6**, wherein said first reflector comprises a reflective coating, wherein said second reflector comprises a reflective coating.

* * * * *

EXHIBIT B

US007522343B2

(12) United States Patent
Hsieh

(10) **Patent No.: US 7,522,343 B2**
(45) **Date of Patent: Apr. 21, 2009**

(54) **MICHELSON INTERFEROMETER BASED DELAY LINE INTERFEROMETERS**

(75) Inventor: **Yung-Chieh Hsieh**, San Jose, CA (US)

(73) Assignee: **Optoplex Corporation**, Fremont, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **11/485,653**

(22) Filed: **Jul. 11, 2006**

(65) **Prior Publication Data**

US 2007/0070505 A1 Mar. 29, 2007

Related U.S. Application Data

(63) Continuation-in-part of application No. 11/360,959, filed on Feb. 22, 2006, and a continuation-in-part of application No. 10/796,512, filed on Mar. 8, 2004, now Pat. No. 7,145,727.

(60) Provisional application No. 60/698,584, filed on Jul. 11, 2005, provisional application No. 60/748,096, filed on Dec. 5, 2005, provisional application No. 60/786,630, filed on Mar. 27, 2006, provisional application No. 60/655,548, filed on Feb. 23, 2005, provisional application No. 60/689,867, filed on Jun. 10, 2005.

(51) **Int. Cl.**
G02B 27/14 (2006.01)

(52) **U.S. Cl.** **359/634**; 359/629

(58) **Field of Classification Search** 359/627–634, 359/578; 398/159, 141, 158, 208; 356/477; 250/339.02

See application file for complete search history.

(56) **References Cited**

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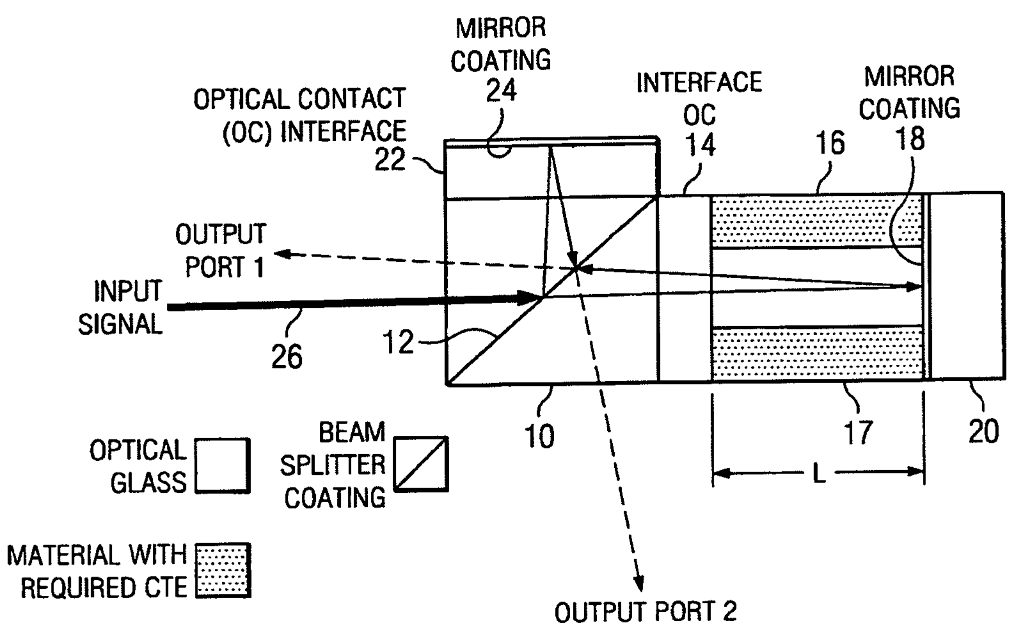
Primary Examiner—Mohammed Hasan
(74) *Attorney, Agent, or Firm*—John P. Wooldridge; Antonio R. Durando

(57) **ABSTRACT**

An interferometer includes a means for splitting, at a splitting location, an input light beam into a first beam and a second beam; and means for recombining, at a recombination location, the first beam and the second beam. The interferometer is designed such that the first beam will travel a first optical path length (OPL) from the splitting location to the recombination location, and the second beam will travel a second OPL from the splitting location to the recombination location and such that when the input light beam has been modulated at a data rate comprising a time interval, then the difference in optical path lengths between the first OPL and the second OPL is about equal to the time interval multiplied by the speed of light.

13 Claims, 6 Drawing Sheets



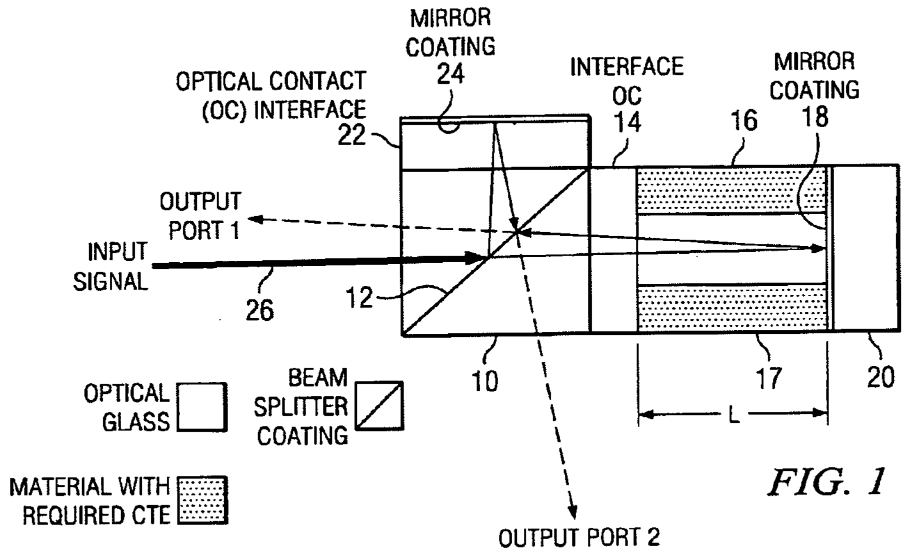

MIRROR COATING 24
OPTICAL CONTACT (OC) INTERFACE 22
INTERFACE OC 14
16
MIRROR COATING 18
OUTPUT PORT 1
INPUT SIGNAL
26
12
10
17
20
L
OPTICAL GLASS
BEAM SPLITTER COATING
MATERIAL WITH REQUIRED CTE
OUTPUT PORT 2

FIG. 1

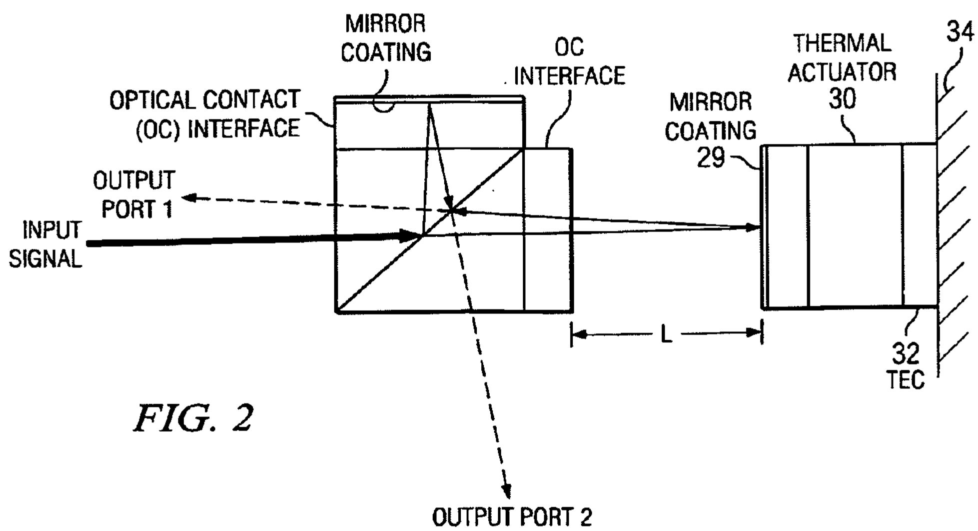

MIRROR COATING
OPTICAL CONTACT (OC) INTERFACE
OC INTERFACE
MIRROR COATING 29
THERMAL ACTUATOR 30
34
OUTPUT PORT 1
INPUT SIGNAL
L
32 TEC
OUTPUT PORT 2

FIG. 2

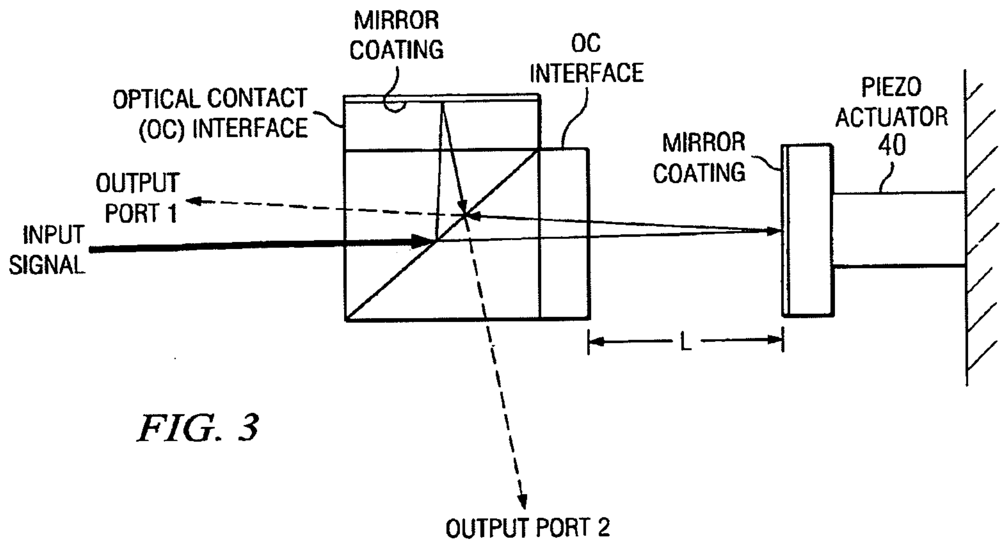

MIRROR
COATING
OC
INTERFACE
OPTICAL CONTACT
(OC) INTERFACE
PIEZO
ACTUATOR
40
MIRROR
COATING
OUTPUT
PORT 1
INPUT
SIGNAL
L
OUTPUT PORT 2

FIG. 3

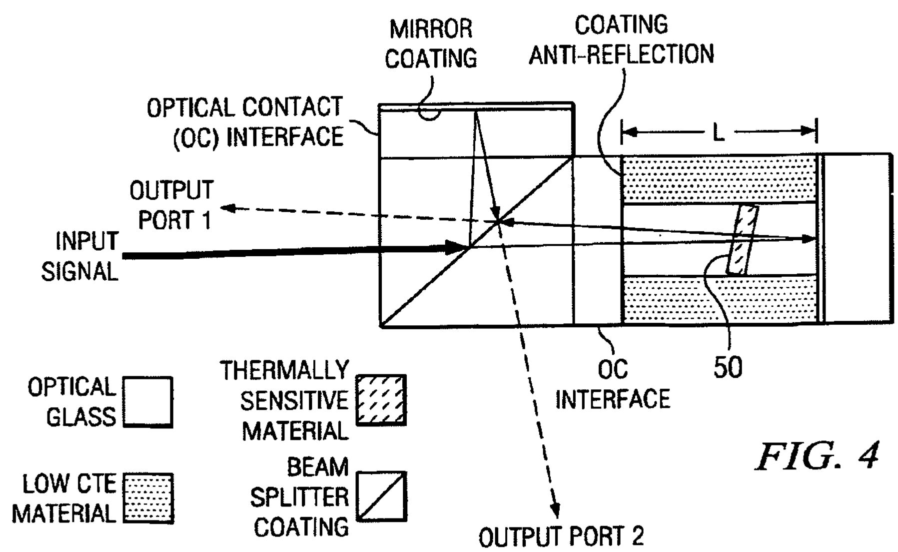

MIRROR
COATING
COATING
ANTI-REFLECTION
OPTICAL CONTACT
(OC) INTERFACE
L
OUTPUT
PORT 1
INPUT
SIGNAL
OC
INTERFACE
50
OPTICAL
GLASS
THERMALLY
SENSITIVE
MATERIAL
LOW CTE
MATERIAL
BEAM
SPLITTER
COATING
OUTPUT PORT 2

FIG. 4

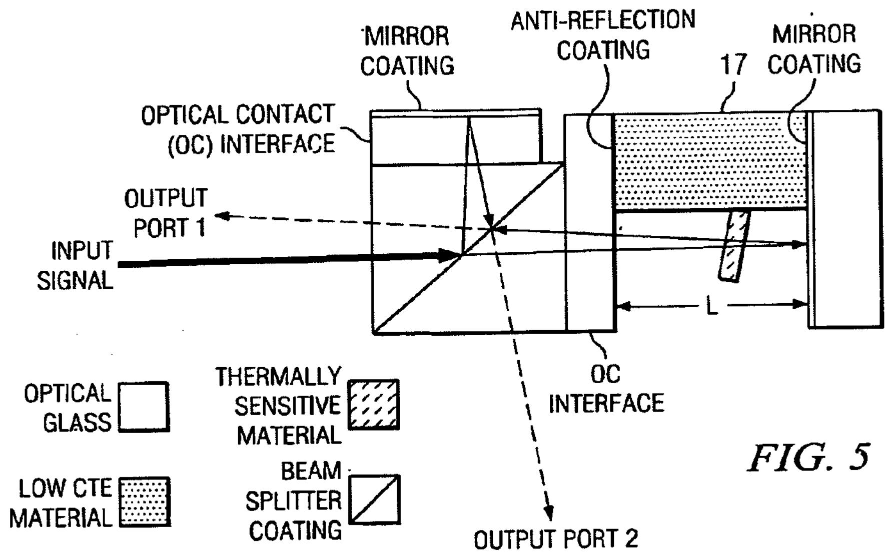


FIG. 5

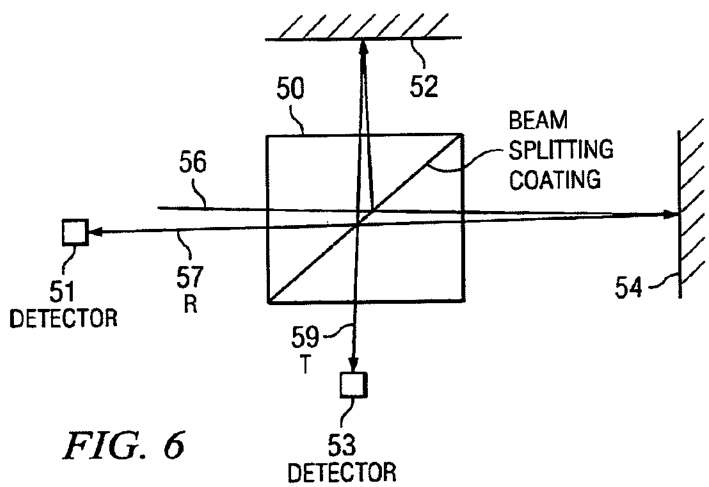


FIG. 6

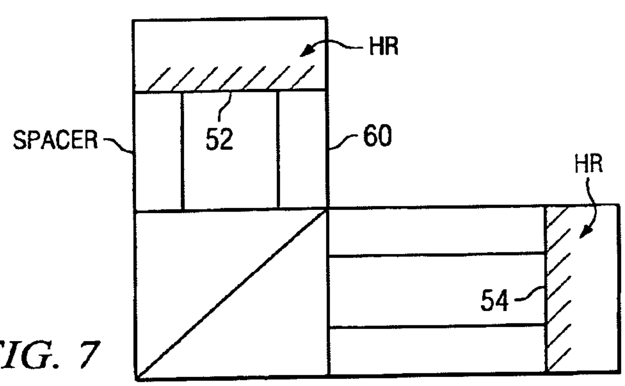


FIG. 7

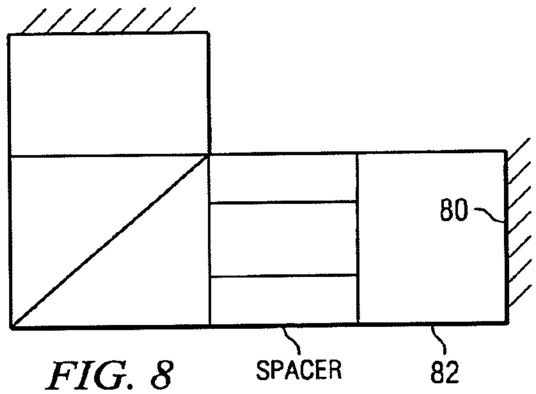


FIG. 8

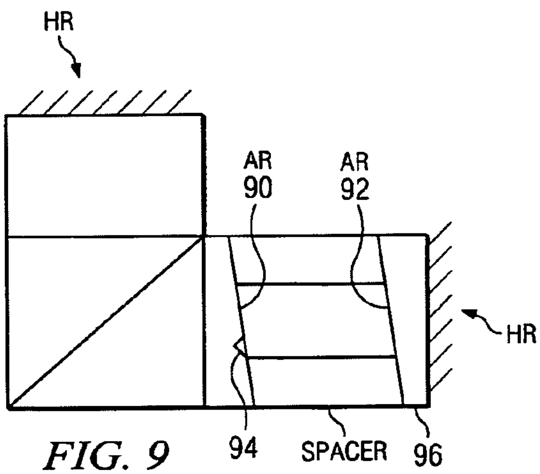


FIG. 9

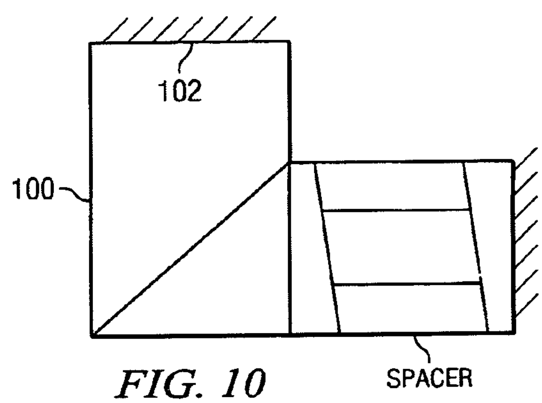


FIG. 10

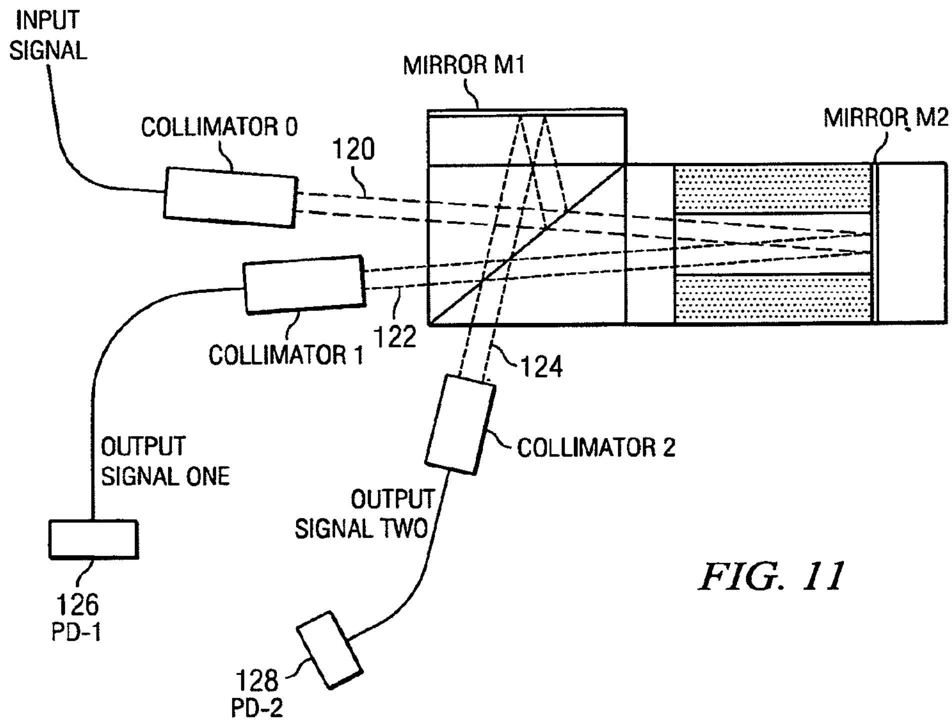

INPUT SIGNAL
MIRROR M1
COLLIMATOR 0
120
MIRROR M2
COLLIMATOR 1
122
124
OUTPUT SIGNAL ONE
COLLIMATOR 2
OUTPUT SIGNAL TWO
126
PD-1
128
PD-2

FIG. 11

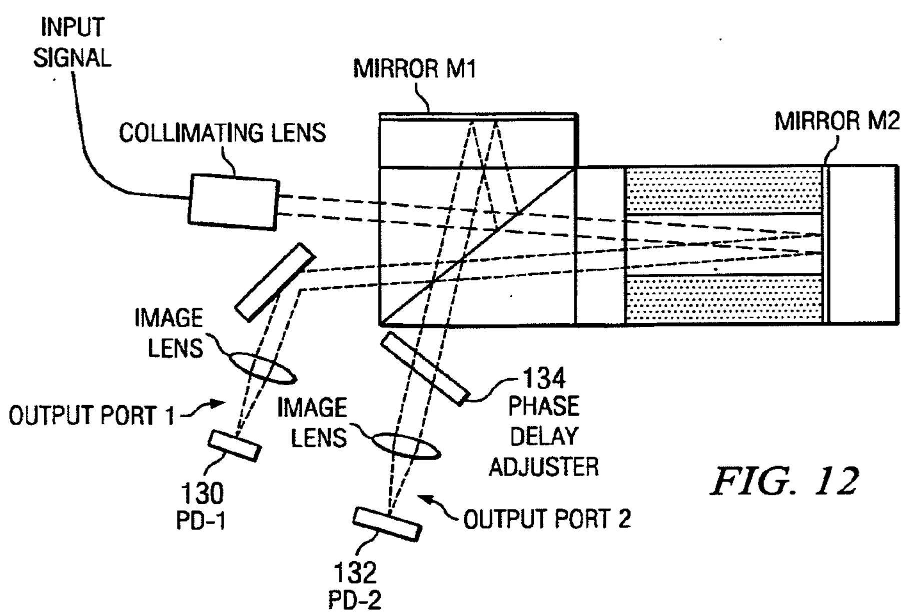

INPUT SIGNAL
MIRROR M1
COLLIMATING LENS
MIRROR M2
IMAGE LENS
134
PHASE DELAY ADJUSTER
OUTPUT PORT 1
IMAGE LENS
130
PD-1
OUTPUT PORT 2
132
PD-2

FIG. 12

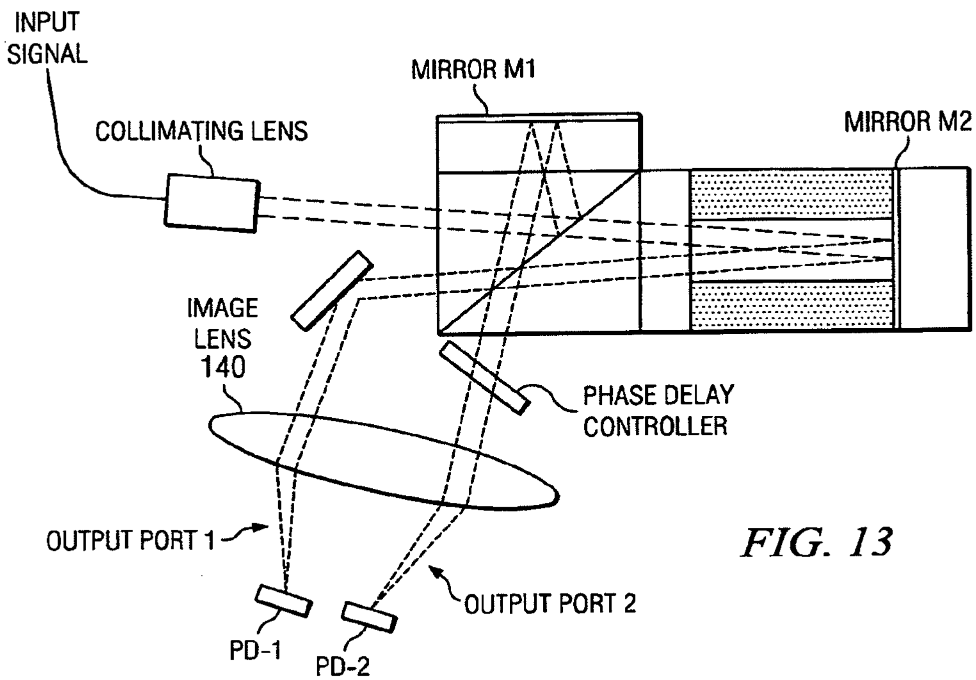

INPUT
SIGNAL
COLLIMATING LENS
MIRROR M1
MIRROR M2
IMAGE
LENS
140
PHASE DELAY
CONTROLLER
OUTPUT PORT 1
OUTPUT PORT 2
PD-1
PD-2

FIG. 13

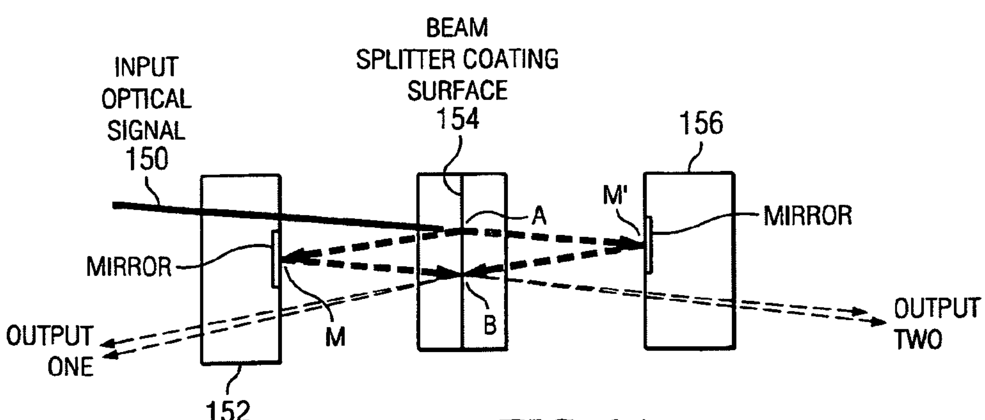

BEAM
SPLITTER COATING
SURFACE
154
INPUT
OPTICAL
SIGNAL
150
156
A
M'
MIRROR
MIRROR
M
B
OUTPUT
ONE
OUTPUT
TWO
152

FIG. 14

MICHELSON INTERFEROMETER BASED DELAY LINE INTERFEROMETERS

This application also claims priority to U.S. Provisional Patent Application Ser. No. 60/698,584, filed Jul. 11, 2005, titled: "Integration of Michelson Differential Phase Shift Keying (DPSK) Demodulator with Photo Detector," incorporated herein by reference. This application also claims priority to U.S. Provisional Patent Application Ser. No. 60/748,096, filed Dec. 5, 2005, titled: "Co-package DQPSK Demodulator by Michelson Interferometer," incorporated herein by reference. This application also claims priority to U.S. Provisional Patent Application Ser. No. 60/786,630, filed Mar. 27, 2006, titled: "Free-Space Optical Hybrid," incorporated herein by reference. This is a continuation-in-part of U.S. patent application Ser. No. 10/796,512, filed Mar. 8, 2004, now U.S. Pat. No. 7,147,727 titled: "Unpolarized Beam Splitter Having Polarization-Independent Phase Difference When Used As An Interferometer," incorporated herein by reference. This is a continuation-in-part of U.S. patent application Ser. No. 11/360,959, filed Feb. 22, 2006, titled "Michelson Interferometer Based Delay Line Interferometers," incorporated herein by reference. This application claims priority to U.S. Provisional Patent Application Ser. No. 60/655,548, filed Feb. 23, 2005, titled: "Athermal Optical Decoder For DPSK," incorporated herein by reference. This application also claims priority to U.S. Provisional Patent Application Ser. No. 60/689,867, filed Jun. 10, 2005, titled: "DPSK by Michelson interferometer," incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to differential phase-shift keying (DPSK) in telecommunication, and more specifically, it relates to methods in DPSK for converting a phase-keyed signal to an intensity-keyed signal.

2. Description of Related Art

Phase-shift keying (PSK) is a digital modulation scheme that conveys data by changing, or modulating, the phase of a reference signal (the carrier wave). Any digital modulation scheme uses a finite number of distinct signals to represent digital data. In the case of PSK, a finite number of phases are used. Each of these phases is assigned a unique pattern of binary bits. Usually, each phase encodes an equal number of bits. Each pattern of bits forms the symbol that is represented by the particular phase. The demodulator, which is designed specifically for the symbol-set used by the modulator, determines the phase of the received signal and maps it back to the symbol it represents, thus recovering the original data. This requires the receiver to be able to compare the phase of the received signal to a reference signal—such a system is termed coherent.

Alternatively, instead of using the bit patterns to set the phase of the wave, it can instead be used to change it by a specified amount The demodulator then determines the changes in the phase of the received signal rather than the phase itself. Since this scheme depends on the difference between successive phases, it is termed differential phase-shift keying (DPSK). DPSK can be significantly simpler to implement than ordinary PSK since there is no need for the demodulator to have a copy of the reference signal to determine the exact phase of the received signal (it is a non-coherent scheme).

In telecommunication technology, differential phase-shift keying (DPSK) requires a decoding method in order to convert the phase-keyed signal to an intensity-keyed signal at the receiving end. The decoding method can be achieved by comparing the phase of two sequential bits. In principle, it splits the input signal beam into two channels with a small delay before recombining them. After the recombination, the beams from the two channels interfere constructively or destructively. The interference intensity is measured and becomes the intensity-keyed signal. To achieve this, one channel has an optical path longer than the other one by a distance equivalent to the photon flight time of one bit. For instance, in a 40 Gbit per second system, one bit is equal to 25 ps, and light travels 7.5 mm in that period. In this example, the optical path difference (OPD) between the two channels is 7.5 mm.

The Mach-Zehnder type interferometer with a desired OPD between the two channels is currently used for decoding purposes. Because of the properties of optical interference, a change in OPD can greatly affect interference intensity. Moreover, the optical path in each arm is much longer than its difference. Therefore, a sophisticated temperature control is required to maintain the optical path in each arm in order to assure that the change in the OPD is much less than a small fraction of one wavelength, e.g., ~10 nm. This is difficult and expensive, especially for an interferometer with a long optical path.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a DPSK demodulator that determines the changes in the phase of a received signal (i.e., the difference between successive phases).

It is another object to use various disclosed embodiments of novel Michelson type interferometers as DPSK demodulators to determine the changes in the phase of a received signal.

These and other objects will be apparent based on the disclosure herein.

The invention is various embodiments of novel Michelson type interferometers used as DPSK demodulators to determine the changes in the phase of a received signal. In the demodulator, the input beam is split into two portions at the beam splitter. The two beams travel a different path and are returned by their corresponding reflector. Because the OPL's are different, the two returned beams have a time delay with respect to each other. The difference between the two OPL's is designed to assure that the delay is approximately equal to the time delay of any two successive bits or data symbols.

A general embodiment of the invention is a Michelson type interferometer that includes a means for splitting, at a splitting location, an input light beam into a first beam and a second beam; and means for recombining, at a recombination location, the first beam and the second beam. The interferometer is designed such that the first beam will travel a first optical path length (OPL) from the splitting location to the recombination location, and the second beam will travel a second OPL from the splitting location to the recombination location and such that when the input light beam has been modulated at a data rate comprising a time interval, then the difference in optical path lengths between the first OPL and the second OPL is about equal to the time interval multiplied by the speed of light.

In specific embodiments of the interferometer, the means for recombining can comprise a first reflector positioned to reflect the first beam, and the means for recombining can further comprise a second reflector positioned to reflect the second beam. In this embodiment, one of the reflectors is separated from the splitting location by a distance sufficient to make the difference in optical path lengths between the first OPL and the second OPL to be about equal to the time interval multiplied by the speed of light The separation of the reflector can be accomplished with at least one spacer that can have either a low or a high coefficient of thermal expansion (CTE). In another embodiment, the separated reflector is fixedly attached to means for adjusting the distance.

The invention also contemplates methods of using the different embodiments of interferometers described herein. A general embodiment of the method includes the steps of providing an input light beam modulated at a data rate comprising a time interval; splitting, at a splitting location, said input light beam into a first beam and a second beam; and recombining, at a recombination location, said first beam and said second beam, wherein said first beam travels a first optical path length (OPL) from said splitting location to said recombination location, wherein said second beam travels a second OPL from said splitting location to said recombination location, wherein the difference in optical path lengths between said first OPL and said second OPL is about equal to said time interval multiplied by the speed of light.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated into and form a part of the disclosure, illustrate embodiments of the invention and, together with the description, serve to explain the principles of the invention.

FIG. **1** illustrates a Michelson-based delay line interferometer.

FIG. **2** shows a high speed thermally tuned DLI.

FIG. **3** shows a piezo tuned tunable DLI.

FIG. **4** shows a Michelson-based delay line interferometer that includes a thermally tuned phase modulator inserted in the optical path.

FIG. **5** shows a single-spacer Michelson-based delay line interferometer.

FIG. **6** shows a prior art Michelson interferometer, with two detectors located at a specific distance.

FIG. **7** illustrates the use of a zero thermal expansion material as a spacer to minimize the change in OPD.

FIG. **8** shows a Michelson-based delay line interferometer with a second surface mirror in both paths.

FIG. **9** shows a Michelson-based delay line interferometer with a second surface mirror in both paths and antireflection coatings on wedged optical elements in one arm.

FIG. **10** shows a beamsplitter with an extended upper arm.

FIG. **11** shows a Michelson DLI with two output ports fiber coupled to photodetectors.

FIG. **12** shows a Michelson DLI with outputs directly coupled to photo detectors.

FIG. **13** shows a Michelson DLI that uses a single lens to directly couple the DLI outputs to photo detectors.

FIG. **14** shows another embodiment utilizing near normal incidence.

DETAILED DESCRIPTION OF THE INVENTION

An embodiment of the present invention is illustrated in FIG. **1**, which shows a Michelson-based delay line interferometer (DLI) formed by a beamsplitter **10** with beamsplitting coating **12** An optical glass element **14** is affixed to the right hand side of the beamsplitter. Element **14** can be affixed, e.g., with an index matching adhesive as known in the art. Spacers **16** and **17**, having a length L, and made of a material having a low coefficient of thermal expansion (CTE), are affixed to the right hand side of the optical element **14**. To the right hand side of the spacers is a mirror coating **18** on a substrate **20**. A second optical glass element **22** is affixed to the top of beamsplitter **10**. A mirror (reflective) coating **24** is located on the second surface of element **22**. When elements **14** and **22** are of the same material and thickness, the round-trip optical path length difference (OPD) between mirror coating **18** and mirror coating **24** is 2 times L, where L is the length of the spacer **16**. The input signal **26** is impingent on the left-hand side of the beamsplitter. Beamsplitting coating **12** splits the light into two beams and each beam carries about 50% of the total power. After each beam is reflected by its corresponding mirror, it hits the beamsplitter in its respective return path, and therefore two beams are split into 4 beams. Interference occurs in both the leftward and the downward beams to form the two output beams of the DLI. The relationship between the free-spectral-range (FSR) and OPD is:

$$FSR = \frac{C}{(OPD)},$$

where C is the speed of light. To make the DLI spectrum to not change with temperature, the CTE of the material that is used for the spacer(s) has to be extremely small. Materials like Zerodur or ULE, e.g., can be used. Both materials have a CTE that is about 0.05 ppm.

A second embodiment that can be understood with reference to FIG. **1** is a thermally tunable DLI. To make the spectrum of the DLI tunable, the material used for the spacers **16** and **17** should have an appropriately high CTE such that when the temperature changes, the OPD will increase or decrease. It turns out that the spectrum of the DLI shifts accordingly. The temperature of the DLI can be adjusted with a thermal electric cooler (TEC) or with a heater.

FIG. **2** shows another type of thermally tuned DLI. In this case, a mirror substrate **28** (between the mirror coating **29** and the actuator) with a mirror coating **29** is mounted on a thermal actuator **30**. The thermal actuator is a material with an appropriate CTE. The TEC **32** is used to provide the heat to or remove the heat from the actuator to adjust the temperature. As shown in FIG. **2**, the left hand side of the TEC is connected to the actuator and its right hand side contacts to a heat sink **34**. When the temperature of the actuator increases, the thermal expansion moves the mirror to the left hand side. For a given temperature change, to maximize the movement, the CTE of the actuator has to be large. Moreover, the response time of this device is determined by how long the heat takes to propagate across the actuator. Therefore, to minimize the response time, a material of high thermal conductivity, e.g., Aluminum or Copper is recommended. One can use Aluminum Nitride with a mirror coating on it to replace the combinational function of the mirror substrate **28** and the actuator **30**, because it has high thermal conductivity, low CTE and excellent surface quality.

The DLI of FIG. **2** has much higher tuning speed and low power consumption than the tunable embodiment of FIG. **1** in which the whole piece of glass must be heated or cooled to tune the spectrum.

FIG. **3** shows a Piezo tuned DLI. The right mirror is mounted to a Piezo actuator **40**. When a voltage is applied across the actuator, the length of the actuator varies according to the magnitude of applied voltage. The frequency response of the device can be easily higher than one KHz. The advantage of this approach is in its high speed and low power consumption.

FIG. **4** shows a DLI whose structure is similar to the device shown in FIG. **1**. In this case, there is a thermally tuned phase modulator **50** inserted in the optical path and the temperature of the phase modulator can be adjusted by a TEC or by heat, which is not shown in the diagram. Spacers of this device are low CTE material. The only thermally sensitive part is the phase modulation window inserted in the optical path. The window material should be optically transparent and the g-factor is a function of temperature.

Assuming that the index and thickness of the phase modulator are n and L_0 respectively, the single trip optical path length is

$$OPL=L+(n-1)L_0.$$

When the temperature changes, the OPL variation is:

$$\begin{aligned}\frac{d[OPL]}{dT} &= \frac{dL}{dT}+(n-1)\frac{dL_0}{dT}+L_0\frac{dn}{dT}\\ &= 0+L_0\left[(n-1)\alpha+\frac{dn}{dT}\right]\\ &= L_0 g\end{aligned}$$

where

$$g=\left[(n-1)\alpha+\frac{dn}{dT}\right],$$

where α is the coefficient of thermal expansion of the phase modulator. In the deviation, it has assumed that the spacer material has zero thermal expansion, i.e., dL/dT=0. The g-factor is a material property. For fused silica glass and Silicon, the g-factor is about 10 ppm/deg-C and 200 ppm/deg-C respectively. If the material is silicon, with a thickness of 100 μm, one can change the OPL by 20 nm with one degree of temperature change.

The embodiment of FIG. **4** has lower power consumption and a higher tuning speed than those of the tunable embodiment of FIG. **1**. The TEC/heat is only applied to a thin piece of phase modulation window **50**, rather than the entire spacer. FIG. **5** shows a single-spacer (**17**) Michelson-based delay line interferometer. The phase modulation window can be used to provide tunability when configured as taught in U.S. Pat. No. 6,816,315, which is incorporated herein by reference.

The polarization dependent property of a Michelson DLI is determined by the beam splitter coating. In order to minimize the PDF (polarization dependent frequency shift), the coating on the beam splitter should have minimized polarization dependent phase (PDP). To achieve this, the coating has to be symmetrical. See U.S. Pat. No. 6,587,204, incorporated herein by reference and U.S. patent application Ser. No. 10/796,512, incorporated herein by reference.

It is well known that a Michelson interferometer includes one beamsplitter **50** and two mirrors **52** and **54**, as shown in FIG. **6**. When light **56** is provided from a coherent light source (such as a laser), the interference intensity can be described as

$$I=A+B\cos(4\pi L\upsilon/C),$$

where C is the speed of light, υ is the optical frequency of the light source, A and B are two constants determined by the two mirrors and the beam splitter, and L equals one half of the OPD between the two arms. For a given υ, the interference intensity is a function of L. The challenge is to hold the two mirrors steadily, i.e., to less than a fraction of one wavelength, over a temperature range from −5 to 70 degree C. The two beams reflected by the two mirrors interfere at the beam splitter, constructively or destructively, and form two output beams, **57** and **59** in FIG. **6**. The interference intensities of these two output beams are complementary. One should also note that the time of flight from the beamsplitter coating to the corresponding detectors (**51** and **53**) is important The time difference between them should be much less than the duration of one bit For use in DQPSK embodiments, the invention is designed to identify phase changes of 0, 90, 180 and 270 degrees.

In order to reduce the thermal and dispersion issue that might be caused by the glass material, two arms should have the same length of glass, and hence their OPD comes mainly from the difference of the air path. This OPD is equal to a distance that is equivalent to the needed time delay. In a hermetically sealed condition, the length of the air path is affected by the spacer used. (Tunability can be provided by providing a gas within the hermetically sealed chamber and providing a mechanism, e.g., a vacuum/pressure pump to change the pressure within the chamber.) As shown in FIG. **7**, the use of a zero thermal expansion material, such as Zerodur or ULE, as the spacer **60**, the change in OPD can be minimized or reduced. Because the two beams experience the same glass path length, with the aid of the zero expansion spacer this design is athermal. Many variations can be derived from this design. For instance, by removing the pair of spacers from one arm, one can achieve the same functionality. This design has been discussed above with reference to FIG. **1**. FIG. **8** shows an embodiment similar to FIG. **1** except that the mirror **80** in the right arm is located on the back surface of optical element **82** FIG. **9** is similar to FIG. **8** except that it includes antireflection coatings **90** and **92** on wedged optical elements **94** and **96**, respectively. The wedges and AR coatings prevent reflections from those surfaces. In FIG. **9**, the right arm has wedged optical elements with antireflection coatings on them. Note that the upper arm can be constructed with the same antireflection wedges. FIG. **10** provides a beamsplitter **100** with an extended upper arm and a mirror coating **102**. The right arm of this embodiment is identical to that of FIG. **9**.

BACKGROUND

FIG. **11** shows a Michelson DLI that is a 3 port device having one input **120** and two outputs **122** and **124**. Typically, all three ports are fiber coupled. The light of the two output ports are each connected to a photo detector (**126**, **128**), which converts the optical signals into electronic signals.

FIG. **12** shows an embodiment of the present invention that integrates the DPSK demodulator with a pair of photo detectors. In other words, instead of coupling the two output signals into fibers, the two output light signals are sent to the photo-detectors (**130**, **132**) directly. Since the optical path lengths from the input port to the two output ports have to be almost identical, in one of the optical paths there is a phase delay adjuster **134**. To adjust the optical path length, one can vary the thickness of the flat or the incident angle to the plate. This approach is advantageous because the size and cost of the receiver can be reduced significantly. Further, the coupling loss to the detector is smaller than to the fiber, thereby reducing the insertion loss of the receiver.

FIG. **13** shows a design that is similar to that of FIG. **12**, but with two detectors that share one lens **140**. This configuration allows the two detectors to be very close to each other.

FIG. **14** shows another embodiment utilizing near normal incidence. The optical path length difference of AMB and AM'B is equal to speed of light multiplied by the time duration of two adjacent bits. In the figure, input beam **150** passes through optical flat **152**, and is split at point A of beam splitter coating **154**. One of the split beams is then reflected from mirror coating M on optical flat **152**, and the other beam is reflected from M', which is a coating on a second optical flat **156**. The beams are recombined at point B of beam splitter coating **154** to form two output channels **158** and **160**. In this case, each output channel includes two beams. The optical path difference between the two spit beams can be changed by changing the distance from coating M to beam splitter coating **154** relative to the distance from coating M' to beam splitter coating **154**. Alternate methods for varying the phase of the two split beams can be used, e.g., a phase adjusting optic such as used in FIG. **12** can be inserted in one of the split beams. Other methods will be apparent to those skilled in the art based on this disclosure.

The foregoing description of the invention has been presented for purposes of illustration and description and is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. For example, for use in QDPSK embodiments, the invention can be designed to identify phase changes of 0, 90, 180 and 270 degrees. The embodiments disclosed were meant only to explain the principles of the invention and its practical application to thereby enable others skilled in the art to best use the invention in various embodiments and with various modifications suited to the particular use contemplated. The scope of the invention is to be defined by the following claims.

I claim:

1. An interferometer, comprising:

means for splitting, at a splitting location, an input light beam into a first beam and a second beam;

means for recombining, at a recombination location, said first beam and said second beam to produce at least one output beam, wherein said first beam will travel a first optical path length (OPL) from said splitting location to said recombination location, wherein said second beam will travel a second OPL from said splitting location to said recombination location, wherein when said input light beam carries phase modulated data with a fixed time interval between two adjacent data symbols, then the difference in optical path lengths between said first OPL and said second OPL is about equal to said time interval multiplied by the speed of light;

a photodetector for detecting each said output beam, wherein said at least one output beam is coupled into said photodetector without at least one fiber optic between said recombination location and said photodetector; and

at least one lens operatively positioned between said recombination location and said photodetector.

2. The interferometer of claim **1**, wherein said means for splitting comprises a non-polarizing beamsplitter (NPB).

3. The interferometer of claim **1**, wherein said means for splitting and said means for recombining comprise one beamsplitter.

4. An interferometer, comprising:

means for splitting, at a splitting location, an input light beam into a first beam and a second beam;

means for recombining, at a recombination location, said first beam and said second beam to produce at least one output beam, wherein said first beam will travel a first optical path length (OPL) from said splitting location to said recombination location, wherein said second beam will travel a second OPL from said splitting location to said recombination location, wherein when said input light beam carries phase modulated data with a fixed time interval between two adjacent data symbols, then the difference in optical path lengths between said first OPL and said second OPL is about equal to said time interval multiplied by the speed of light; and

means for detecting each said output beam, wherein said at least one output beam comprises a first output beam and a second output beam, said interferometer further comprises means for adjusting the phase of one of said first output beam or said second output beam.

5. An interferometer, comprising:

means for splitting, at a splitting location, an input light beam into a first beam and a second beam;

means for recombining, at a recombination location, said first beam and said second beam to produce at least one output beam, wherein said first beam will travel a first optical path length (OPL) from said splitting location to said recombination location, wherein said second beam will travel a second OPL from said splitting location to said recombination location, wherein when said input light beam carries phase modulated data with a fixed time interval between two adjacent data symbols, then the difference in optical path lengths between said first OPL and said second OPL is about equal to said time interval multiplied by the speed of light; and

means for detecting each said output beam, wherein said interfereometer comprises a first optic comprising a first portion that is transparent to a wavelength of interest and a second portion that is reflective to said wavelength, a beam splitter with a beam splitter coating and a second optic comprising a third portion that is transparent to said wavelength and a fourth portion that is reflective to said wavelength, wherein said beam splitter coating is utilized as both said means for splitting and said means for recombining.

6. An interferometer, comprising:

means for splitting, at a splitting location, an input light beam into a first beam and a second beam;

means for recombining, at a recombination location, said first beam and said second beam to produce at least one output beam, wherein said first beam will travel a first optical path length (OPL) from said splitting location to said recombination location, wherein said second beam will travel a second OPL from said splitting location to said recombination location, wherein when said input light beam carries phase modulated data with a fixed time interval between two adjacent data symbols, then the difference in optical path lengths between said first OPL and said second OPL is about equal to said time interval multiplied by the speed of light; and

means for detecting each said output beam, wherein said means for recombining comprise a first reflector positioned to reflect said first beam, wherein said means for recombining further comprise a second reflector positioned to reflect said second beam.

7. The interferometer of claim **6**, wherein one of said first reflector and said second reflector is separated from said splitting location by a distance sufficient to make the difference in optical path lengths between said first OPL and said second OPL to be about equal to said time interval multiplied by the speed of light.

8. The interferometer of claim **6**, wherein one of said first reflector and said second reflector is separated with at least one spacer from said splitting location by a distance sufficient to make the difference in optical path lengths between said first OPL and said second OPL to be about equal to said time interval multiplied by the speed of light.

9. The interferometer of claim **8**, wherein said at least one spacer comprises a material having a low coefficient of thermal expansion (CTE).

10. The interferometer of claim **8**, wherein said at least one spacer comprises a material having a high coefficient of thermal expansion.

11. The interferometer of claim **6**, wherein one of said first reflector and said second reflector is a separated reflector that is separated from said splitting location by a distance sufficient to make the difference in optical path lengths between said first OPL and said second OPL to be about equal to said time interval multiplied by the speed of light, wherein said separated reflector is fixedly attached to means for adjusting said distance.

12. The interferometer of claim **6**, further comprising a thermally tunable phase modulator for adjusting the optical path length of said first OPL or said second OPL.

13. The interferometer of claim **6**, wherein said first reflector comprises a reflective coating, wherein said second reflector comprises a reflective coating.

* * * * *