

COHERENT OPTICAL DETECTOR HAVING A MULTIFUNCTIONAL WAVEGUIDE GRATING

CROSS-REFERENCE TO RELATED APPLICATIONS

5 The subject matter of this application is related to the subject matters of U.S. Patent Application No. 12/229,983, filed 08/28/2008, and entitled "Monolithic Coherent Optical Detectors" and U.S. Patent Application No. 12/338,492, filed 12/18/2008, and entitled "Optical Mixer for Coherent Detection of Polarization-Multiplexed Signals," both of which are incorporated herein by reference in their entirety.

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BACKGROUND

Field of the Invention

 The present invention relates to optical communication equipment and, more specifically but not exclusively, to coherent detectors for optical receivers.

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Description of the Related Art

 This section introduces aspects that may help facilitate a better understanding of the invention(s). Accordingly, the statements of this section are to be read in this light and are not to be understood as admissions about what is in the prior art or what is not in the prior art.

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 A coherent optical-detection scheme is capable of detecting not only the amplitude of an optical signal, but also the signal's polarization and phase. These capabilities make coherent optical detection compatible with polarization-division multiplexing and with the use of spectrally efficient modulation formats, such as quadrature amplitude modulation (QAM) and phase-shift keying (PSK) in its various forms (e.g., differential PSK (DPSK) and differential quadrature PSK (DQPSK)). Compared to incoherent detectors, coherent optical detectors offer relatively easy wavelength tunability, good rejection of interference from adjacent channels in dense wavelength-division-multiplexing (DWDM) systems, linear transformation of the electromagnetic field into an electrical signal for effective application of modern digital signal processing techniques, and an opportunity to use polarization-division multiplexing. As a result, coherent optical detectors are currently being actively developed.

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SUMMARY

Disclosed herein are various embodiments of a coherent optical detector having a waveguide circuit, in which a plurality of waveguides are connected to a waveguide grating. In a representative embodiment, the waveguide grating serves at least three different functions, e.g., those of a fiber-optic coupler, a polarization splitter, and two power splitters, one for each of two orthogonal polarizations. Various embodiments of the coherent optical detector can be used to demodulate various forms of polarization-division-multiplexed (PDM) QAM- and/or PSK-modulated optical communication signals.

According to one embodiment, provided is an apparatus having a first waveguide grating and a first plurality of waveguides connected to the first waveguide grating. The first plurality comprises a first waveguide and a second waveguide collinear with the first waveguide at the first waveguide grating. Optical power of a first polarization of a first optical signal applied to the first waveguide grating is split and coupled by the first waveguide grating into the first and second waveguides. If the first optical signal comprises a component having a first carrier wavelength, then optical power of the first polarization of that component is split and coupled by the first waveguide grating into the first and second waveguides.

BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects, features, and benefits of various embodiments of the invention will become more fully apparent, by way of example, from the following detailed description and the accompanying drawings, in which:

Figs. 1A-B schematically show a differential optical detector according to one embodiment of the invention;

Fig. 2 shows a schematic top view of a differential optical detector according to another embodiment of the invention; and

Fig. 3 shows a schematic top view of a coherent optical detector according to yet another embodiment of the invention.

DETAILED DESCRIPTION

Figs. 1A-B schematically show a differential optical detector **100** according to one embodiment of the invention. More specifically, Fig. 1A shows a schematic top view of

detector **100**. Fig. 1B shows an enlarged top view of a fiber-optic coupling region **140** of detector **100**. Detector **100** can be used, e.g., for optical differential phase-shift-keying (DPSK) demodulation of polarization-division multiplexed (PDM) communication signals. Alternatively or in addition, detector **100** can be used for demodulation of a non-
5 PDM DPSK communication signal in a polarization-independent manner. As known in the art, a DPSK demodulator operates to convert an optical DPSK signal into an intensity-keyed signal and is usually used at a receiver of a fiber-optic communication network. As used herein, the term “PDM signal” refers to an optical signal that comprises two independently modulated components having the same wavelength, but
10 orthogonal states of polarization.

Detector **100** has a waveguide circuit **110** that is optically coupled, via two 2x2 optical couplers **120a-b**, to four photo-detectors (e.g., photodiodes) **130a-d**. In one embodiment, waveguide circuit **110**, optical couplers **120a-b**, and photo-detectors **130a-d** are all implemented in a monolithic photonic integrated circuit (PIC) using integration
15 techniques disclosed, e.g., in the above-cited U.S. Patent Application No. 12/229,983. Other known integration techniques may likewise be used.

Referring to Fig. 1B, coupling region **140** of waveguide circuit **110** has a waveguide grating **142**. In a representative embodiment, grating **142** comprises a plurality of cavities, pillars, and/or holes **144** etched into or formed on an upper surface of
20 a ridge waveguide to form a two-dimensional, rectangular or square pattern. Each of the four sides of grating **142** is connected to a corresponding one of ridge waveguides **112a-d**. In coupling region **140**, waveguides **112a-b** are collinear with each other and orthogonal to waveguides **112c-d**, which are similarly collinear with each other. A grating that can be used as grating **142** is disclosed, e.g., in U.S. Patent No. 7,065,272,
25 which is incorporated herein by reference in its entirety.

In detector **100**, grating **142** serves at least three different functions, e.g., those of (1) a fiber-optic coupler, (2) a polarization splitter, and (3) two power splitters, one for each of two orthogonal polarizations of the optical input signal. More specifically, if grating **142** is physically abutted with a single-mode optical fiber, e.g., oriented
30 orthogonally with respect to the upper surface of the grating (i.e., perpendicular to the plane of Figs. 1A-B), then light from the optical fiber will couple, with relatively low losses, from the optical fiber into waveguides **112a-d**, hence the fiber-optic-coupler

functionality of grating **142**. If the light in the optical fiber has two polarization components, e.g., an X-polarization component and a Y-polarization component, then the X-polarization component will couple into waveguides **112a-b** and the Y-polarization component will couple into waveguides **112c-d**, hence the polarization-splitter

5 functionality of grating **142**. The coupled optical power of the X polarization will be divided substantially evenly between waveguides **112a-b**, hence the power-splitter functionality of grating **142** for the X polarization. Similarly, the coupled optical power of the Y polarization will be divided substantially evenly between waveguides **112c-d**, hence the power-splitter functionality of grating **142** for the Y polarization. Note that, if
10 the optical input signal has a single carrier wavelength, then all three of the above-described functions apply to the signal component having that carrier wavelength. If the optical input signal has multiple carrier wavelengths, then each of the signal components corresponding to different carrier wavelengths is subjected to each of the three above-described functions.

15 The fiber-optic coupling efficiency of grating **142** can be optimized for any selected wavelength or a range of wavelengths by using a corresponding appropriate pattern of cavities or holes **144**. For example, the above-cited U.S. Patent No. 7,065,272 discloses patterns that can be used for efficiently coupling light having wavelengths between about 1500 nm and about 1600 nm. One skilled in the art will appreciate that, to
20 obtain a grating suitable for efficient coupling of other wavelengths, the disclosed patterns can be modified, e.g., by appropriately changing the periodicity of cavities or holes in the grating.

In a representative embodiment of waveguide circuit **110**, the X polarization from an abutted optical fiber efficiently couples into and propagates along each of waveguides
25 **112a-b** as a corresponding transverse electric (TE) waveguide mode. The X polarization couples into waveguides **112c-d** relatively inefficiently, and this coupling is negligible for all practical purposes. Similarly, the Y polarization from the abutted optical fiber couples (i) efficiently into each of waveguides **112c-d** as a corresponding TE waveguide mode and (ii) negligibly into waveguides **112a-b**.

30 Referring back to Fig. 1A, for each of the X and Y polarizations of an optical communication signal applied to grating **142**, detector **100** achieves DPSK demodulation by comparing the phases of two sequential bits. For example, grating **142** splits the X

polarization of the incoming DPSK signal into two beams and couples those beams into waveguides **112a-b**, respectively, which direct the beams to 2x2 optical coupler **120a**. Waveguides **112a-b** have an optical-path difference that introduces a time delay corresponding to the optical-symbol period (bit length) of the DPSK signal when the two beams arrive at the input side of optical coupler **120a**. Optical coupler **120a** coherently recombines the received beams to produce two optical interference signals corresponding to adjacent optical bits of the DPSK signal. The two interference signals are applied to photo-detectors **130a-b**, respectively, which are coupled to the output side of optical coupler **120a**. Photo-detectors **130a-b** convert each of the interference signals into a corresponding intensity-keyed electrical signal. In one embodiment, photo-detectors **130a-b** are electrically connected, as known in the art, to implement a balanced detection scheme. The Y polarization of the incoming DPSK signal is processed in detector **100** similar to the X polarization, but in the detector portion having waveguides **112c-d**, 2x2 optical coupler **120b**, and photo-detectors **130c-d**. If detector **100** receives a PDM optical communication signal, then the electrical signals generated by photo-detectors **130a-b** are treated as corresponding to one of the PDM data streams, and the electrical signals generated by photo-detectors **130c-d** are treated as corresponding to one another of the PDM data streams. If detector **100** receives a non-PDM signal, then the electrical signals generated by photo-detectors **130a-b** and **130c-d** can be added together to produce a response that is substantially independent of the state of polarization of the optical communication signal.

Waveguides **112a** and **112c** intersect to create a waveguide crossing **114**. The angle between waveguides **112a** and **112c** in waveguide crossing **114** is typically between about 80 and about 100 degrees. In one embodiment, to reduce crosstalk between waveguides **112a** and **112c**, waveguide crossing **114** incorporates one or more multimode-interference (MMI) lenses as disclosed, e.g., in U.S. Patent No. 7,058,259, which is incorporated herein by reference in its entirety.

An optical communication link between the remote transmitter and detector **100** imposes a generally uncontrolled polarization rotation onto the DPSK signal before this signal is applied to waveguide grating **142**. However, digital signal-processing (DSP) techniques can be used, as known in the art, to process the electrical signals generated by photo-detectors **130a-d** in a manner that substantially compensates for that polarization

rotation and enables the receiver having detector **100** to fully recover two independent, PDM data streams carried by the DPSK signal. Representative DSP techniques that can be adapted to achieve the requisite polarization-rotation compensation is disclosed, e.g., in U.S. Patent Application Publication Nos. 2008/0152362 and 2008/0152363, both of which are incorporated herein by reference in their entirety.

Fig. 2 shows a schematic top view of a differential optical detector **200** according to another embodiment of the invention. Detector **200** can be used, e.g., for optical differential quadrature-phase-shift-keying (DQPSK) demodulation of PDM communication signals or polarization-insensitive demodulation of non-PDM communication signals. As known in the art, DQPSK modulation uses transitions between four points on a constellation diagram, the points being equispaced on a circle centered on the origin. With four different phase increments (i.e., 0, 90, 180, and -90 degrees) corresponding to various possible transitions, DQPSK encodes two bits per transition.

Similar to detector **100**, detector **200** employs waveguide circuit **110**. However, detector **200** differs from detector **100** in that, in detector **200**, waveguide circuit **110** is optically coupled to two 2x4 optical couplers **220a-b** rather than 2x2 optical couplers **120a-b**. The four output ports of each optical coupler **220** are coupled to four corresponding photo-detectors **230**. The use of a 2x4 optical coupler acting as an optical 90-degree hybrid for the demodulation of a DQPSK signal is disclosed, e.g., in U.S. Patent No. 7,343,104, which is incorporated herein by reference in its entirety. Briefly, the two input signals to a 2x4 optical coupler interfere therein so that the output port(s) at which the interference signal appears depends on the phase difference between the input signals. As a result, the signals generated by the four photo-detectors **230** coupled to a 2x4 optical coupler **220** can be used to unambiguously determine the phase increment between two consecutive optical DQPSK symbols and, hence, the corresponding two bits encoded thereby.

In detector **200**, waveguide circuit **110** performs polarization splitting as described above in reference to Fig. 1. Optical coupler **220a** and the four photo-detectors **230** coupled thereto perform demodulation of the X polarization of the DQPSK communication signal applied to grating **140**. Similarly, optical coupler **220b** and the

four photo-detectors **230** coupled thereto perform demodulation of the Y polarization of that DQPSK communication signal.

Fig. 3 shows a schematic top view of a coherent optical detector **300** according to yet another embodiment of the invention. Detector **300** can be used, e.g., for optical quadrature-phase-shift-keying (QPSK) or QAM reception of PDM communication signals. As known in the art, QPSK modulation uses four points on a constellation diagram, which points are equispaced on a circle centered on the origin. QAM modulation uses two carrier waves that are out of phase with each other by about 90 degrees. These waves are usually referred to as the in-phase and quadrature-phase components of the QAM signal. QPSK modulation can be considered as a special case of QAM modulation and is often referred to as 4-QAM. The number of bits encoded by a QAM symbol depends on the constellation size and can be two, three, or more bits per optical symbol.

Detector **300** has a waveguide circuit **310** that is optically coupled, via four 2x2 optical couplers **320a-d**, to eight photo-detectors **330**. Optical couplers **320** and photo-detectors **330** of detector **300** are analogous to optical couplers **120** and photo-detectors **130**, respectively, of detector **100** (see Fig. 1). Unlike waveguide circuit **110**, waveguide circuit **310** has two coupling regions **340a-b**, each having a waveguide grating **342** that is similar to waveguide grating **142** (see Fig. 1B). Each waveguide grating **342** is connected to four corresponding waveguides **312**. Note that Fig. 3 is drawn not to scale and, at each grating **342**, the corresponding waveguides **312** are arranged in an orthogonal/collinear manner, e.g., as indicated in Fig. 1B.

All waveguides **312** have the same path length between the corresponding waveguide grating **342** and the input side of the corresponding optical coupler **320**. Each of waveguides **312d-e** has a corresponding one of phase shifters **316a-b**. In one embodiment, each phase shifter **316** comprises an electrode deposited over the core of the corresponding waveguide **312**. If the electrode is biased, then the electric field generated due to the bias induces a corresponding change in the refraction index of the material of the waveguide core, which changes the phase shift for the light wave traveling along the waveguide. Electrical leads connected to photo-detectors **330** and phase shifters **316** are omitted in Fig. 3 for clarity. Waveguide circuit **310** has two waveguide crossings **314**,

each of which is analogous to waveguide crossing **114** of waveguide circuit **110** (see Fig. 1).

In operation, coupling regions **340a-b** are used to couple a received (e.g., QAM) optical communication signal and a local oscillator (LO) signal, respectively, into detector **300**. In a representative coupling arrangement, an optical fiber carrying the optical communication signal is abutted with waveguide grating **342a** in coupling region **340a**. Another optical fiber carrying the LO signal is similarly abutted with waveguide grating **342b** in coupling region **340b**. Both optical fibers are oriented perpendicular to the plane of waveguide circuit **310** (i.e., perpendicular to the plane of Fig. 3).

In a representative configuration of detector **300**, the polarization of the LO signal is chosen so that the electric-field vector is parallel to a diagonal of waveguide grating **342b**. One skilled in the art will appreciate that this state of polarization results in approximately equal LO power being coupled into each of waveguides **312b,d,e,g**. Each of phase shifters **316a-b** is biased to apply a 90-degree phase shift to the LO signal directed from waveguide grating **342b** to the corresponding one of optical couplers **320b** and **320c**. One purpose of having phase shifter **316b** is to ensure that the relative phase shift between two interferometer arms having waveguides **312a-b** is equal to the relative phase shift between two interferometer arms having **312e-f** plus or minus 90 degrees. Similarly, one purpose of phase shifter **316a** is to ensure that the relative phase shift between two interferometer arms having waveguides **312c-d** is equal to the relative phase shift between two interferometer arms having waveguides **312g-h** plus or minus 90 degrees. In one embodiment, phase shifter **316a** can be moved from waveguide **312d** to waveguide **312c**, **312g**, or **312h**. A similar relocation is possible for phase shifter **316b**. More generally, various embodiments of detector **100** may have two variously located phase shifters, as long as those phase shifters are associated with the interferometers that process different polarizations.

In one embodiment, the eight photo-detectors **330** in detector **300** are electrically connected, e.g., as disclosed in the above-cited U.S. Patent Application Nos. 12/229,983 and 12/338,492 and U.S. Patent Application Publication Nos. 2008/0152362 and 2008/0152363, to form four balanced photo-detector pairs. More specifically, each balanced photo-detector pair has two photo-detectors **330** coupled to the same optical coupler **320**. The balanced photo-detector pair coupled to optical coupler **320a** detects an

optical signal produced by the interference of an X-polarization component of the optical communication signal applied to grating **342a** and an X-polarization component of the LO signal applied to grating **342b**. The balanced photo-detector pair coupled to optical coupler **320b** detects an optical signal produced by the interference of a Y-polarization component of the optical communication signal applied to grating **342a** and a 90-degree phase-shifted Y-polarization component of the LO signal applied to grating **342b**. The balanced photo-detector pair coupled to optical coupler **320c** detects an optical signal produced by the interference of an X-polarization component of the optical communication signal applied to grating **342a** and a 90-degree phase-shifted X-polarization component of the LO signal applied to grating **342b**. The balanced photo-detector pair coupled to optical coupler **320d** detects an optical signal produced by the interference of a Y-polarization component of the optical communication signal applied to grating **342a** and a Y-polarization component of the LO signal applied to grating **342b**. As a result, these four balanced photo-detector pairs of detector **300** measure (i) the in-phase component IX of the X polarization, (ii) the quadrature-phase component QY of the Y polarization, (iii) the quadrature-phase component QX of the X polarization, and (iv) the in-phase component IY of the Y polarization, respectively, of the optical communication signal applied to grating **342a**.

The present inventions may be embodied in other specific apparatus and/or methods. The described embodiments are to be considered in all respects as only illustrative and not restrictive. In particular, the scope of the invention is indicated by the appended claims rather than by the description and figures herein. All changes that come within the meaning and range of equivalency of the claims are to be embraced within their scope. For example, although various coherent optical detectors of the invention were described in reference to PDM signals, certain principles of the invention are also applicable to demodulation of non-PDM signals. Various coherent optical detectors can be implemented as corresponding monolithic PICs, including implementations as substantially planar receiver cards or circuits. In one embodiment, a waveguide circuit of the invention can be implemented using silicon waveguides. Although embodiments of the invention were described in reference to ridge waveguides, other types of waveguides can also be used. Known DSP techniques can be used to process the electrical signals generated by the photo-detectors of the coherent optical detector in a manner that substantially compensates for the polarization rotation in the fiber link and enables the

optical receiver to fully recover two independent PDM data streams carried by the received optical communication signal.

The description and drawings merely illustrate the principles of the invention. It will thus be appreciated that those of ordinary skill in the art will be able to devise
5 various arrangements that, although not explicitly described or shown herein, embody the principles of the invention and are included within its spirit and scope. Furthermore, all examples recited herein are principally intended expressly to be only for pedagogical purposes to aid the reader in understanding the principles of the invention and the concepts contributed by the inventor(s) to furthering the art, and are to be construed as
10 being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass equivalents thereof.

It should be appreciated by those of ordinary skill in the art that any block diagrams herein represent conceptual views of illustrative circuitry embodying the
15 principles of the invention. Similarly, it will be appreciated that any flow charts, flow diagrams, state transition diagrams, pseudo code, and the like represent various processes which may be substantially represented in computer readable medium and so executed by a computer or processor, whether or not such computer or processor is explicitly shown.

Unless explicitly stated otherwise, each numerical value and range should be
20 interpreted as being approximate as if the word "about" or "approximately" preceded the value of the value or range.

It will be further understood that various changes in the details, materials, and arrangements of the parts which have been described and illustrated in order to explain the nature of this invention may be made by those skilled in the art without departing
25 from the scope of the invention as expressed in the following claims.

Although the elements in the following method claims, if any, are recited in a particular sequence with corresponding labeling, unless the claim recitations otherwise imply a particular sequence for implementing some or all of those elements, those elements are not necessarily intended to be limited to being implemented in that particular
30 sequence.

Reference herein to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment can be included in at least one embodiment of the invention. The

appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments necessarily mutually exclusive of other embodiments. The same applies to the term "implementation."

5 Throughout the detailed description, the drawings, which are not to scale, are illustrative only and are used in order to explain, rather than limit the invention. The use of terms such as height, length, width, top, bottom, is strictly to facilitate the description of the invention and is not intended to limit the invention to a specific orientation. For example, height does not imply only a vertical rise limitation, but is used to identify one
10 of the three dimensions of a three dimensional structure as shown in the figures. Such "height" would be vertical where the electrodes are horizontal but would be horizontal where the electrodes are vertical, and so on. Similarly, while all figures show the different layers as horizontal layers such orientation is for descriptive purpose only and not to be construed as a limitation.

15 Also for purposes of this description, the terms "couple," "coupling," "coupled," "connect," "connecting," or "connected" refer to any manner known in the art or later developed in which energy is allowed to be transferred between two or more elements, and the interposition of one or more additional elements is contemplated, although not required. Conversely, the terms "directly coupled," "directly connected," etc., imply the
20 absence of such additional elements.

CLAIMS

What is claimed is:

1. An apparatus, comprising:
a first waveguide grating; and
5 a first plurality of waveguides connected to the first waveguide grating, wherein:
the first plurality comprises a first waveguide and a second waveguide collinear
with the first waveguide at the first waveguide grating; and
optical power of a first polarization of a first optical signal applied to the first
waveguide grating is split and coupled by the first waveguide grating into the first and
10 second waveguides.
2. The apparatus of claim 1, wherein, if the first optical signal comprises a
component having a first carrier wavelength, then optical power of the first polarization
of said component is split and coupled by the first waveguide grating into the first and
15 second waveguides.
3. The apparatus of claim 1, wherein:
the first plurality further comprises a third waveguide orthogonal to the first and
second waveguides at the first waveguide grating; and
20 optical power of a second polarization of the first optical signal is coupled by the first
waveguide grating into the third waveguide, the second polarization being orthogonal to
the first polarization.
4. The apparatus of claim 3, wherein:
25 the first plurality further comprises a fourth waveguide collinear with the third
waveguide at the first waveguide grating; and
the optical power of the second polarization of the first optical signal is split and
coupled by the first waveguide grating into the third and fourth waveguides.
- 30 5. The apparatus of claim 4, further comprising a first optical coupler and a second
optical coupler, wherein:
the first and second waveguides are connected to a first side of the first optical
coupler;

the third and fourth waveguides are connected to a first side of the second optical coupler;

the first waveguide has a first length between the first waveguide grating and the first optical coupler;

5 the second waveguide has a second length between the first waveguide grating and the first optical coupler, the second length being different from the first length;

the third waveguide has the first length between the first waveguide grating and the second optical coupler; and

10 the fourth waveguide has the second length between the first waveguide grating and the second optical coupler.

6. The apparatus of claim 5, wherein:

the first optical signal is characterized by an optical-symbol period; and

15 a difference in optical-signal propagation time through the first and second lengths of waveguide is approximately the optical-symbol period.

7. The apparatus of claim 5, further comprising a plurality of photo-detectors coupled to a second side of the first optical coupler and a second side of the second optical coupler.

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8. The apparatus of claim 7, wherein, if the first optical signal is a polarization-division-multiplexed (PDM) differential phase-shift-keying (DPSK) signal, then the photo-detectors generate electrical signals indicative of data carried by the PDM DPSK signal.

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9. The apparatus of claim 7, wherein, if the first optical signal is a polarization-division-multiplexed (PDM) differential quadrature-phase-shift-keying (DQPSK) signal, then the photo-detectors generate electrical signals indicative of data carried by the PDM DQPSK signal.

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10. The apparatus of claim 1, further comprising an optical coupler, wherein:

the first and second waveguides are connected to a first side of the optical coupler;

the first waveguide has a first length between the first waveguide grating and the optical coupler; and

the second waveguide has a second length between the first waveguide grating and the optical coupler, the second length being different from the first length.

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11. The apparatus of claim 10, wherein:

the first optical signal is characterized by an optical-symbol period; and

a difference in optical-signal propagation time through the first and second lengths of waveguide is approximately the symbol period.

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12. The apparatus of claim 10, further comprising two photo-detectors coupled to a second side of the optical coupler, wherein, if the first optical signal is a differential phase-shift-keying (DPSK) signal, then the two photo-detectors generate electrical signals indicative of data carried by the DPSK signal.

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13. The apparatus of claim 10, further comprising four photo-detectors coupled to a second side of the optical coupler, wherein, if the first optical signal is a differential quadrature-phase-shift-keying (DQPSK) signal, then the four photo-detectors generate electrical signals indicative of data carried by the DQPSK signal.

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14. The apparatus of claim 1, wherein:

the first grating comprises a ridge waveguide having on a surface a plurality of cavities or holes that form a periodic two-dimensional pattern; and

the first optical signal is applied to said surface.

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15. The apparatus of claim 1, wherein the first waveguide grating and the first plurality of waveguides are implemented in a monolithic photonic integrated circuit.

16. The apparatus of claim 1, further comprising:

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a second waveguide grating; and

a second plurality of waveguides connected to the second waveguide grating, wherein:

the second plurality comprises a first waveguide and a second waveguide collinear with the first waveguide at the second waveguide grating; and

optical power of the first polarization of a second optical signal applied to the second waveguide grating is split and coupled by the second waveguide grating into the first and second waveguides of the second plurality.

5 17. The apparatus of claim 16, wherein:

the first plurality comprises a third waveguide and a fourth waveguide orthogonal to the first and second waveguides of the first plurality and collinear with each other at the first waveguide grating;

10 the second plurality comprises a third waveguide and a fourth waveguide orthogonal to the first and second waveguides of the second plurality and collinear with each other at the second waveguide grating;

optical power of a second polarization of the first optical signal is split and coupled by the first waveguide grating into the third and fourth waveguides of the first plurality; and

15 optical power of the second polarization of the second optical signal is split and coupled by the second waveguide grating into the third and fourth waveguides of the second plurality.

18. The apparatus of claim 17, further comprising first, second, third, and fourth optical couplers, wherein:

20 the first waveguide of the first plurality and the first waveguide of the second plurality are connected to a first side of the first optical coupler;

the second waveguide of the first plurality and the second waveguide of the second plurality are connected to a first side of the second optical coupler;

25 the third waveguide of the first plurality and the third waveguide of the second plurality are connected to a first side of the third optical coupler; and

the fourth waveguide of the first plurality and the fourth waveguide of the second plurality are connected to a first side of the fourth optical coupler.

19. The apparatus of claim 18, wherein the first, second, third, and fourth waveguides in the first and second pluralities have equal lengths between the corresponding waveguide grating and the corresponding optical coupler.

20. The apparatus of claim 18, wherein:

the second waveguide of the second plurality comprises a first phase shifter;
the third waveguide of the second plurality comprises a second phase shifter; and
the apparatus further comprises a plurality of photo-detectors coupled to second sides
of the first, second, third, and fourth optical couplers, wherein, if:

- 5 the first optical signal is a polarization-division-multiplexed (PDM) quadrature-
 amplitude-modulation (QAM) signal;
 the second optical signal is a local-oscillator signal; and
 each of the first and second phase shifters sets a corresponding phase difference to
 about 90 degrees,
- 10 then the photo-detectors generate electrical signals indicative of data carried by the PDM
 QAM signal.