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(54) **PHOTODIODE ARRAY WITH ALGORITHM-BASED CROSSTALK REDUCTION**

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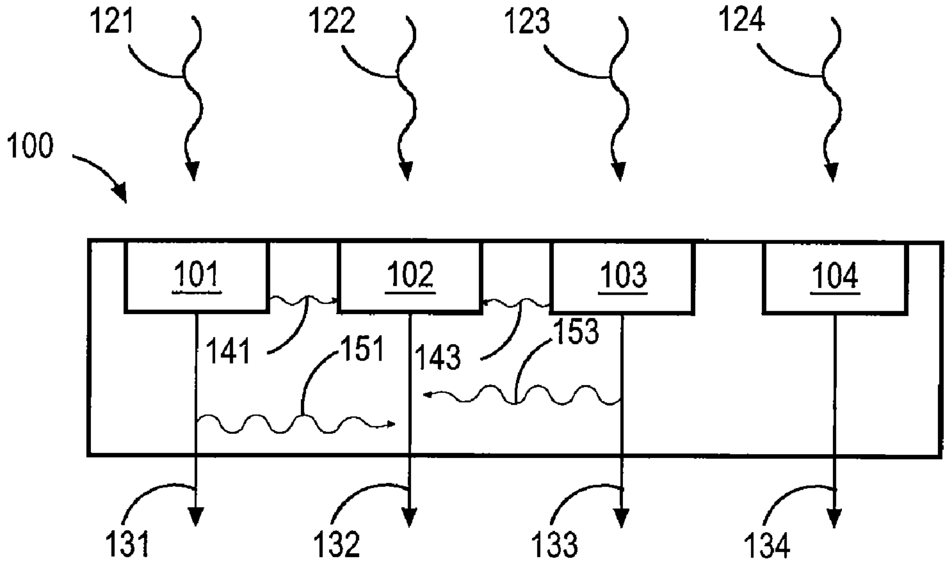
(57) **ABSTRACT**

A photodiode (PD) array accurately measures incident optical power on each of the PDs in the array by eliminating the effect of crosstalk between the individual PDs. Crosstalk within the PD array is removed by measuring the current generated by each PD in the array and generating a corrected optical power value for each PD that is based on the measured current for each PD and on coupling coefficients associated with other PDs in the array. The coupling coefficients are determined during a previous calibration procedure.



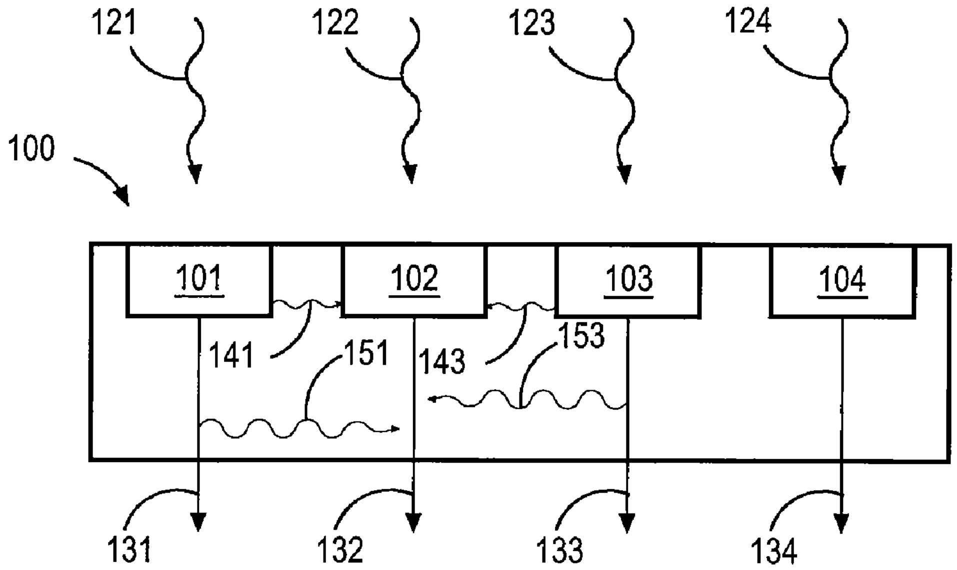

121
122
123
124
100
101
102
103
104
141
151
143
153
131
132
133
134

FIG. 1

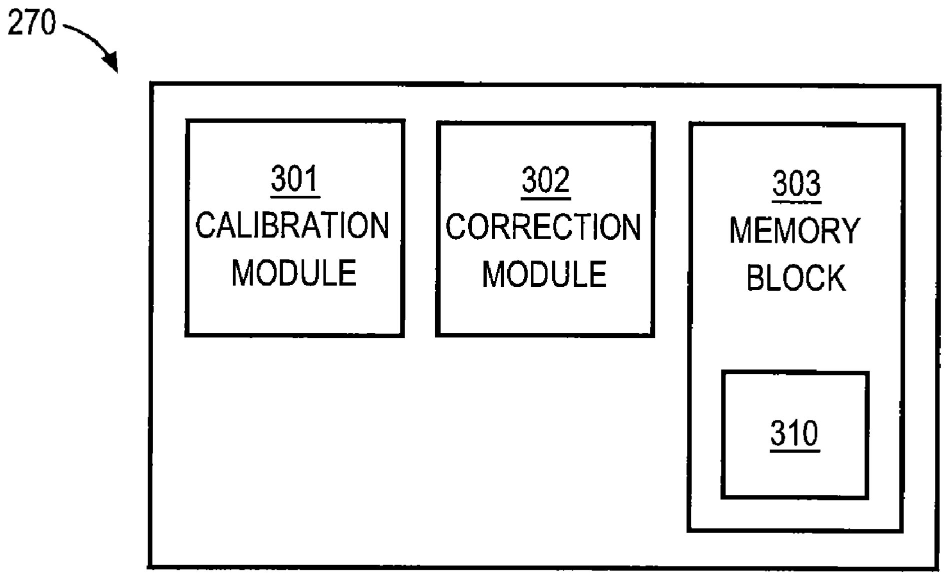

270
301
CALIBRATION MODULE
302
CORRECTION MODULE
303
MEMORY BLOCK
310

FIG. 3

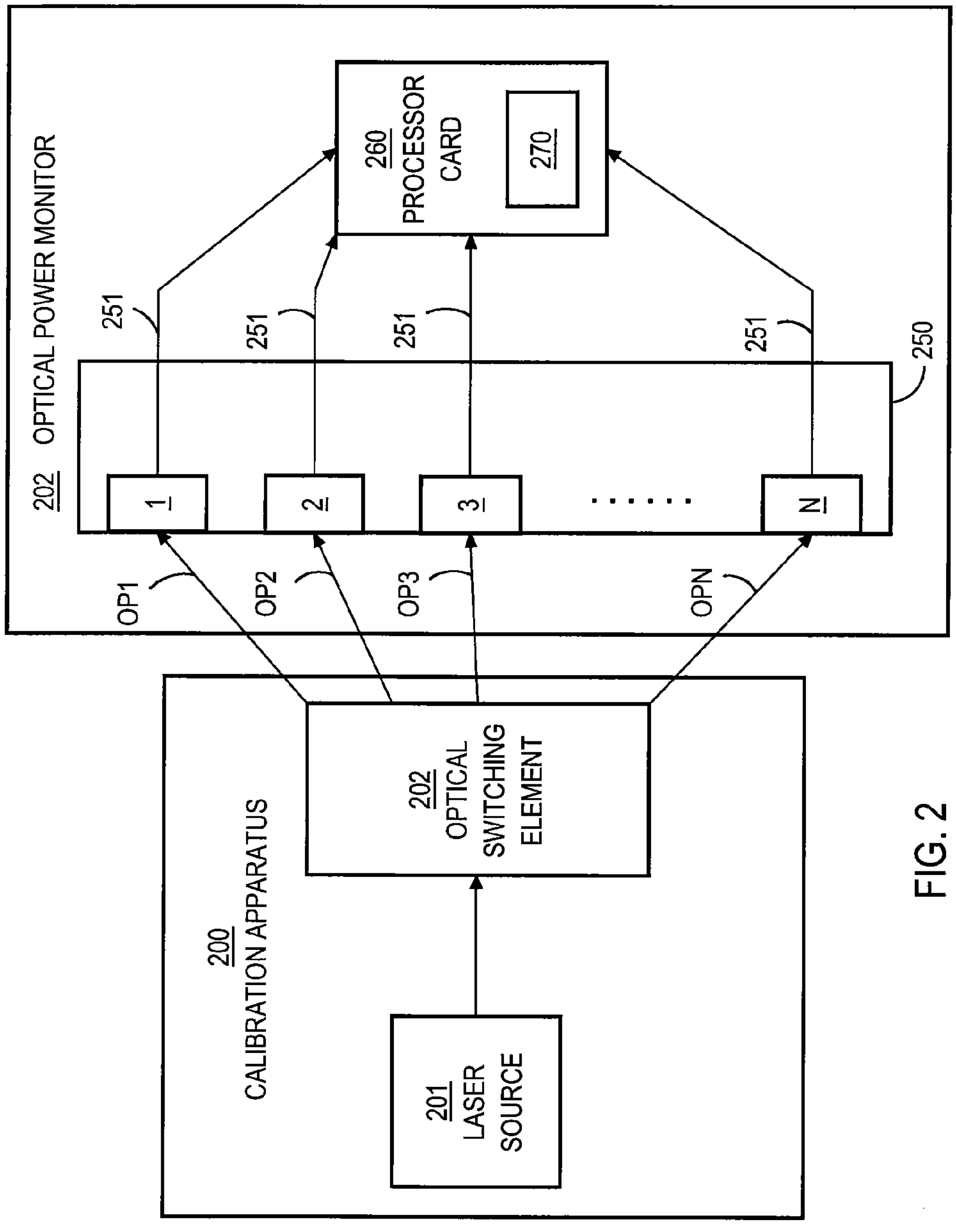

202 OPTICAL POWER MONITOR
260 PROCESSOR CARD
270
251
251
251
251
250
1
2
3
N
OP1
OP2
OP3
OPN
200 CALIBRATION APPARATUS
202 OPTICAL SWITCHING ELEMENT
201 LASER SOURCE

FIG. 2

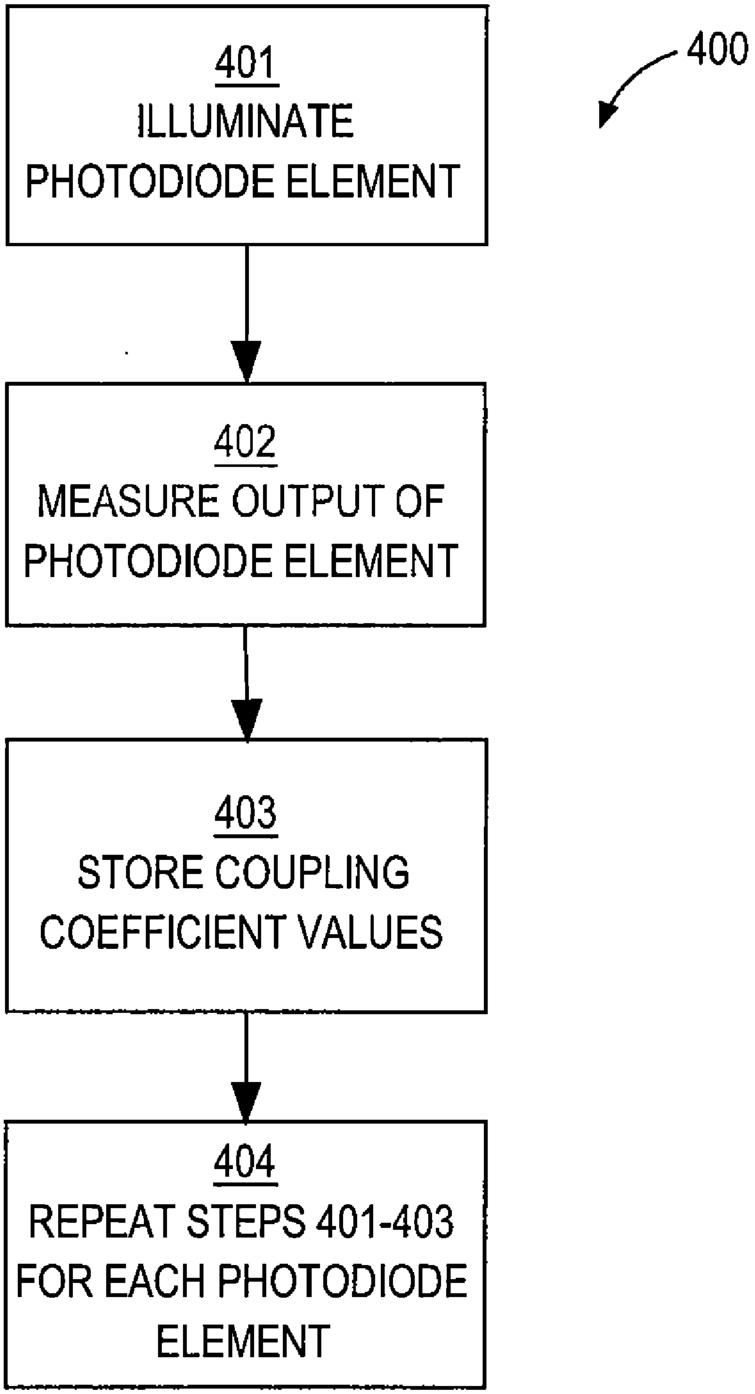

400
401
ILLUMINATE PHOTODIODE ELEMENT
402
MEASURE OUTPUT OF PHOTODIODE ELEMENT
403
STORE COUPLING COEFFICIENT VALUES
404
REPEAT STEPS 401-403 FOR EACH PHOTODIODE ELEMENT

FIG. 4

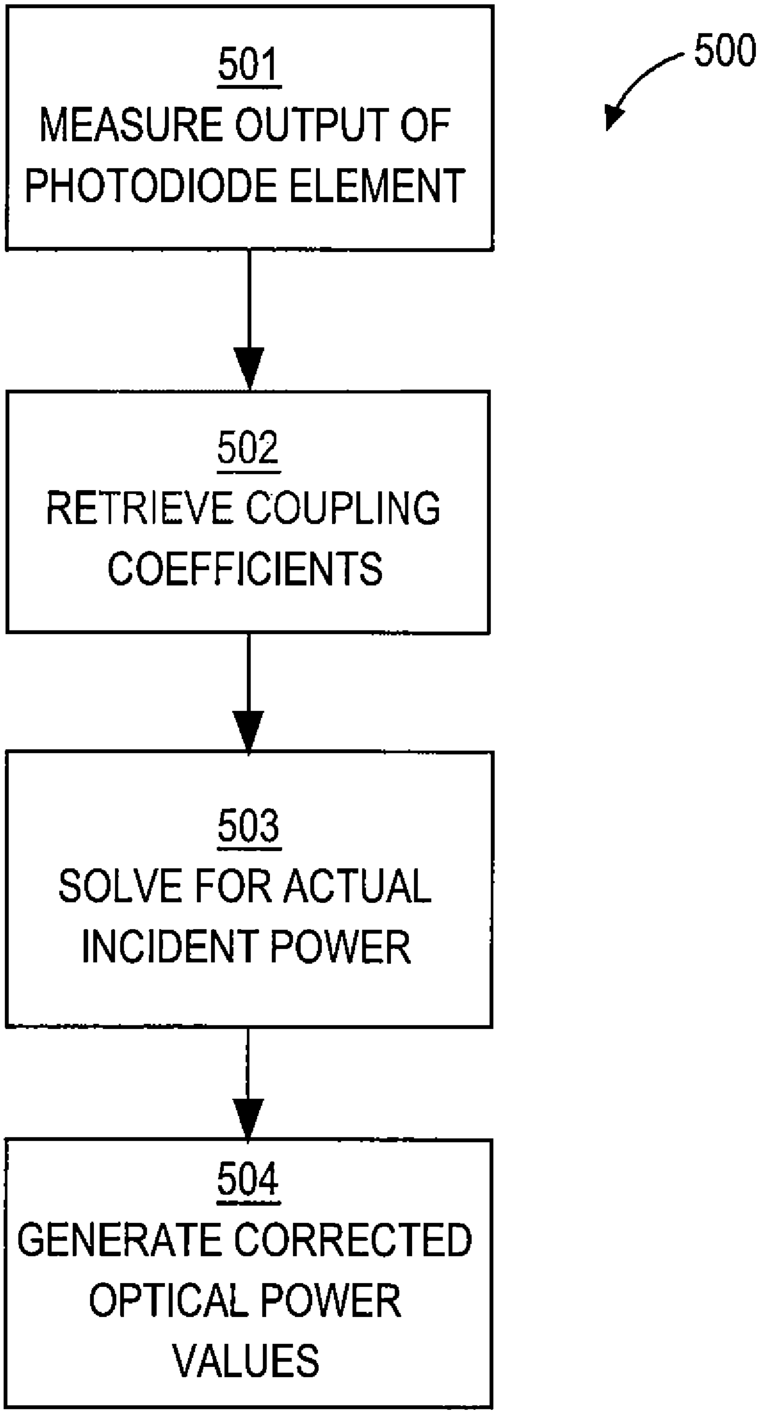

500
501
MEASURE OUTPUT OF PHOTODIODE ELEMENT
502
RETRIEVE COUPLING COEFFICIENTS
503
SOLVE FOR ACTUAL INCIDENT POWER
504
GENERATE CORRECTED OPTICAL POWER VALUES

FIG. 5

PHOTODIODE ARRAY WITH ALGORITHM-BASED CROSSTALK REDUCTION

BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] Embodiments of the present invention relate generally to optical communication systems and components and, more particularly, to a photodiode array with algorithm-based crosstalk reduction.

[0003] 2. Description of the Related Art

[0004] Photodiodes are used to perform optical power measurement and monitoring in a range of devices, including optical amplifiers, wavelength selective switches, and other systems that benefit from the monitoring of optical channel performance. In devices using multiple photodiodes, such as wavelength-division-multiplexing (WDM) devices, the size and cost of the relatively large numbers of photodiodes required can be problematic. Manufacturing multiple photodiodes together as an integrated detector array can greatly reduce the size and unit cost of the photodiodes, such as when a large number of semiconductor photodiodes are fabricated from a common substrate. However, such photodiode arrays are more readily subject to crosstalk between the elements of the array, which can affect the accuracy and resolution of the detector array.

[0005] Crosstalk between adjacent photodiode elements of a detector array is an important parameter of the performance of the array and can be due to either electrical or optical crosstalk. Electrical crosstalk occurs when carriers that are photo-generated by one photodiode element diffuse across a common substrate and are collected by a neighboring photodiode element in the array. Optical crosstalk occurs when the light energy itself is partially incident on neighboring elements, and includes the effects of photon refraction, reflection at boundaries, and external and internal scattering in a photodiode array.

[0006] FIG. **1** schematically illustrates electrical and optical crosstalk occurring in a photodiode array **100**. Photodiode array **100** includes a plurality of photodiodes (PDs) **101**-**104** formed on a common semiconductor substrate **110**. In operation, incident light **121**-**124** strikes PDs **101**-**104**, respectively. In response, each of PDs **101**-**104** produces an electrical output **131**-**134**. Ideally, the amplitude of electrical output **131** is directly proportional to the optical energy contained in incident light **121**, the amplitude of electrical output **132** is directly proportional to the optical energy contained in incident light **122**, and so on. In practice, the electrical output **131**-**134** of each of PDs **101**-**104** is affected by crosstalk from neighboring PDs. For example, in the case of PD **102**, optical leakage **141** from PD **101** and optical leakage **143** from PD **103** will affect the value of electrical output **132** from PD **102**. Similarly, electrical leakage **151** from PD **101** and electrical leakage **153** from PD **103** will also affect the value of electrical output **132** from PD **102**. Thus, the electrical outputs **131**-**134** of photodiode array **100** are inherently inaccurate, particularly when the elements of photodiode array **100** are fabricated on common semiconductor substrate **110**.

[0007] The effect of crosstalk can be reduced between elements of a PD array through structural and other design changes to the PD devices in the array. For example, optical crosstalk can be reduced by the formation of a radiation shield or other optical energy barrier between the PD array elements during the process of fabricating the PD elements. Similarly, electrical crosstalk can be reduced by forming electrical barriers between the PD array elements. However, such techniques add complexity and cost to the manufacturing process. Accordingly, there is a need in the art for PD arrays having reduced crosstalk without the presence of additional structures in the PD array.

SUMMARY OF THE INVENTION

[0008] One or more embodiments of the present invention provide a photodiode (PD) array for measuring incident optical power and a method of accurately measuring optical power of light incident on each of the PDs in such an array. The effect of crosstalk between the individual PDs of the array is removed by measuring the current generated by each PD in the array and generating a corrected optical power value for each PD that is based on the measured current for each PD and on coupling coefficients associated with other PDs in the array, where the coupling coefficients are determined during a previous calibration procedure. In some embodiments, the corrected optical power values may be solved for simultaneously using a system of linear equations, where each equation expresses the measured optical power value for a PD in the array as a function of the corrected optical power value for the PD and the appropriate coupling coefficients.

[0009] In a photodiode array, a method of measuring optical power of light incident on photodiodes according to an embodiment of the present invention comprises measuring a current generated by a photodiode in the array in response to the light incident on the photodiode and generating an optical power value based on the measured current and correction factors associated with other photodiodes in the array.

[0010] A computer-readable storage medium according to another embodiment of the present invention comprises instructions to be executed by a processing unit of an optical power monitoring device to carry out the steps of measuring a current generated by a photodiode in a photodiode array in response to the light incident on the photodiode and generating an optical power value based on the measured current and correction factors associated with other photodiodes in the array.

[0011] According to another embodiment of the present invention, an optical power measuring system comprises a processor and a photodiode array, wherein the processor is configured to perform the steps of measuring a current generated by a photodiode in the photodiode array in response to the light incident on the photodiode, and generating an optical power value based on the measured current and correction factors associated with other photodiodes in the array.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] So that the manner in which the above recited features of the present invention can be understood in detail, a more particular description of the invention, briefly summarized above, may be had by reference to embodiments, some of which are illustrated in the appended drawings. It is to be noted, however, that the appended drawings illustrate only typical embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

[0013] FIG. **1** schematically illustrates electrical and optical crosstalk occurring in a photodiode array.

[0014] FIG. **2** schematically illustrates a calibration apparatus for determining coupling coefficients between photodiode (PD) elements of a PD array, according to embodiments of the invention.

[0015] FIG. **3** schematically illustrates an exemplary embodiment of a processor, according to embodiments of the invention.

[0016] FIG. **4** is a flow chart that summarizes, in a stepwise fashion, a method for determining coupling coefficients between PD elements, according to embodiments of the invention.

[0017] FIG. **5** is a flow chart that summarizes, in a stepwise fashion, a method for measuring optical power of light incident on PDs in a PD array, according to embodiments of the invention.

[0018] For clarity, identical reference numbers have been used, where applicable, to designate identical elements that are common between figures. It is contemplated that features of one embodiment may be incorporated in other embodiments without further recitation.

DETAILED DESCRIPTION

[0019] One or more embodiments of the present invention provide a low-crosstalk photodiode (PD) array for measuring incident optical power and a method for accurately measuring optical power of light incident on each of the PDs in an array that removes the effect of crosstalk. Coupling coefficients quantifying the optical and/or electrical coupling between each PD of the array are determined during a previous calibration procedure and are used to remove the effect of crosstalk on the different outputs of the PD array.

[0020] FIG. **2** schematically illustrates a calibration apparatus **200** for determining coupling coefficients between the PD elements **1**-N of a PD array **250**, according to embodiments of the invention. Calibration apparatus **200** includes a laser source **201** optically coupled to an optical switching element **202**, which is in turn optically coupled to optical power monitor **220**. Laser source **201** is a laser configured to produce optical output in the wavelength band and power range in which the PD elements **1**-N of PD array **250** are intended to operate. The number of PD elements, N, in PD array **250** may be a one-, two-, or three-digit integer or larger. In some embodiments, laser source **201** may be a tunable laser, such as when PD elements **1**-N are configured to measure the optical energy of different bandwidths in a wavelength-division-multiplexing (WDM) application. In such embodiments, laser source **201** may be tuned to the different wavelengths corresponding to particular WDM wavelength channels. Thus, when laser source **201** is a tunable laser source, a calibration procedure may be performed with calibration apparatus **200** to generate a complete set of coupling coefficients between PD elements **1**-N for each wavelength of light that may be directed to PD array **250**. Such a calibration procedure is described in greater detail below. Optical switching element **202** is configured to optically couple laser source **201** to any one of the PD elements **1**-N of PD array **250** with minimal loss via optical paths OP**1**-OPN as shown. Optical paths OP**1**-OPN may be optic fibers, waveguides, free space optical paths, and/or a combination thereof. The optical loss that occurs between optical switching element **202** and each of PD elements **1**-N is known in order to maximize accuracy of the calibration procedure for determining coupling coefficients.

[0021] Optical power monitor **220** includes PD array **250** and a processor card **260**. Optical power monitor **220** is a device that may be used for monitoring optical power of multiple light sources, and may be incorporated into any system or device that includes the function of optical power monitoring. For example, optical power monitor **220** may be an integrated component of an optical amplifier card, a wavelength selective switch, or other performance-monitoring devices used in a WDM application, and may be used to quantify the performance of WDM data channels, optical supervisor channels, etc.

[0022] PD array **250** includes a plurality of N PD elements, each of which is configured to monitor the optical power of light incident thereon. In some embodiments, PD elements **1**-N may be part of a monolithically integrated semiconductor sensor array and fabricated on a common substrate, such as an InP or InSb substrate. When light is incident on one of the PD elements of PD array **250**, the PD element integrates the incident optical energy and produces an electrical output **251** that is proportional to the optical energy in said bandwidth. Thus, in operation, PD array **250** may be utilized as an optical power monitor for a plurality of light sources, such as individual WDM data channels that have been demultiplexed from a WDM optical signal.

[0023] Processor card **260** includes electronic components and other hardware for measuring the electrical output **251** of each PD element **1**-N and is configured to control the normal operation of optical power monitor **220**. Processor card **260** is also configured to perform calibration measurements and the calculation of coupling coefficients between PD elements **1**-N based on said measurements. Processor card **260** further includes a processor **270**, which is configured to perform calculations and execute instructions for the operation and calibration of optical power monitor **220**. Processor **270** can be any appropriate processor including but not limited to general-purpose processors such as microprocessors and digital signal processors (DSP), or a special-purpose processor such as an application specific integrated circuit (ASIC) or field-programmable gate array (FPGA).

[0024] FIG. **3** schematically illustrates an exemplary embodiment of processor **270**, according to embodiments of the invention. Processor **270** includes a calibration module **301**, a correction module **302**, and a memory block **303**. Calibration module **301** is configured to execute the appropriate instructions and computations for optical power monitor **220** to perform calibration procedures and to calculate coupling coefficients between each PD element of PD array **250** and to store these coupling coefficients in memory block **303**. For example, calibration module **301** may be used to control laser source **201** and optical switching element **202** during the calibration procedure. One such calibration procedure for determining coupling coefficients is disclosed below. Correction module **302** is configured to update measured optical power values to actual optical power values by applying coupling coefficients to the optical power values measured by each of PD elements **1**-N and solving for the actual optical power values for each PD element. A method of computing actual optical power values for each PD element is described below in conjunction with FIG. **5**. Calibration module **301** and correction module **302** may be logical modules, dedicated hardware, or a combination of both. Depending on the desired configuration, memory block **303** may be of any type including but not limited to volatile memory (such as RAM), non-volatile memory (such as ROM, flash memory, etc.) or any combination thereof. Coupling coefficients **310** are stored in memory block **303** and are retrieved during normal operation of optical power monitor **220** to eliminate the effect of crosstalk on electrical outputs **251** of PD elements **1**-N.

[0025] In operation, calibration apparatus **200**, when coupled to optical power monitor **220**, determines coupling coefficients between PD elements **1**-N of a PD array **250**. FIG. **4** is a flow chart that summarizes, in a stepwise fashion, a method **400** for determining coupling coefficients between PD elements **1**-N, according to embodiments of the invention. Method **400** is described in terms of an optical power monitoring device substantially similar optical power monitor **220**, described above. However, other optical power monitoring devices may also benefit from the use of method **400**. Although the method steps are described in conjunction with FIG. **4**, persons skilled in the art will understand that any system configured to perform the method steps, in any order, falls within the scope of the present invention. Prior to the first step of method **400**, the optical loss of optical paths OP**1**-OPN is determined, to maximize the accuracy of the coupling coefficients determined in method **400**.

[0026] The method begins in step **401**, in which laser source **201** is coupled to a single PD element via optical switching element **202** and optical path OP**1**. Thus, one PD element is illuminated with a known quantity of optical power and the remaining PD elements are completely "dark," i.e., no incident light energy is directed thereto. For clarity, the illuminated PD element is herein referred to as PD element M, where M may be any of the 1 to N PD elements in PD array **250**.

[0027] In step **402**, processor **270** measures electrical output **251** of each of PD elements **1**-N. Electrical output **251** of the illuminated PD element, i.e., PD element M, is approximately proportional to the optical power of light thereon, but includes significant inaccuracy due to optical and electrical crosstalk from some or all of the other PD elements in PD array **250**. Electrical output **251** of each dark PD element is, within measurement error, exactly proportional to the crosstalk between the PD element M and the dark PD element. The value of each electrical output **251** measured in step **402** can be used as coupling coefficients that together can be used to solve for the actual incident optical power on PD elements **1**-N. The use of coupling coefficients to solve for actual incident power is described below in steps **403**-**405** of method **400** and step **503** of method **500**.

[0028] In step **403**, processor **270** stores the coupling coefficient values measured in step **402** in memory block **303**. Because the coupling coefficient values stored are each proportional to the crosstalk between the dark PD elements and PD element M, these coupling coefficient values may be used in Equation 1. Equation 1 relates the actual optical power $P_{incident}$ that is incident on PD element M to the measured optical power $P_{measured}$ that is reported by PD element M, where $P_{measured}$ includes the effect of crosstalk from all other PD elements in PD array **250** on PD element M:

$$P_{measured}(M)=\sum_{j=1}^{N} C_{Mj}P_{incident}(j) \tag{1}$$

where M is a specific PD element, N is the total number of PD elements in PD array **250**, and c_{Mj} is the coupling coefficient that represents the effect of crosstalk from PD element j on PD element M. It is noted that Equation 1 holds true even when PD element M is not the only PD element in PD array **250** that is being illuminated. By way of example, for the first PD element (M=1) in a 4-element PD array, substitution of the appropriate values into Equation 1 yields Equation 2:

$$P_{measured}(1)=C_{11}P_{inc}(1)+C_{12}P_{inc}(2)+C_{13}P_{inc}(3)+C_{14}P_{inc}(4) \tag{2}$$

[0029] In practice, the contribution to crosstalk to PD element M by other than the closest PD elements in PD array **250** may be negligible. In some embodiments, for simplicity, only the coupling coefficients of PD elements proximate and/or adjacent to PD element M are stored in step **403**, and all other coupling coefficient values are assumed to be zero.

[0030] The series of coupling coefficients stored in step **403**, i.e., c_{M1}, c_{M2}, c_{M3}, . . . c_{MN}, can be used to populate the Mth row of an N×N matrix, herein referred to as a "crosstalk matrix." As described below, the N×N crosstalk matrix can be used to simultaneously solve for the actual incident optical power $P_{incident}$ for each of PD elements **1**-N. In some embodiments, prior to storing the coupling coefficients for PD element M measured in step **402**, PD element M is set as the reference element and the coupling coefficients are normalized to 1 for the self-coupling element in the series. In other words, the coupling coefficient representing the coupling of PD element M to itself is set to one and the remaining coupling coefficient values are adjusted proportionally, i.e., when M=j, $c_{Mj}=1$. This normalization process facilitates later matrix inversion of the crosstalk matrix when solving for the actual incident power $P_{incident}$.

[0031] In step **404**, steps **401**-**403** are repeated for each PD element in PD array **250**, so that each of PD elements **1**-N is treated as element M. In this way, a series of coupling coefficients is collected for each PD element in PD array **250**, so that the N×N crosstalk matrix can be constructed.

[0032] In some applications, crosstalk between PD elements may vary significantly as a function of wavelength. Consequently, the coupling coefficients measured in method **400** may not be accurate when different wavelengths of light are monitored by optical power monitor **220**. In some embodiments, multiple sets of coupling coefficients are measured, where a different set of coupling coefficients is measured for each wavelength or wavelength band of interest. In such embodiments, method **400** is repeated for each wavelength or wavelength band. Subsequently, when optical power monitor **220** is in operation, the crosstalk matrix that is used to solve for the actual incident power $P_{incident}$ is constructed by selecting the appropriate coupling coefficients for each PD element from the different wavelength-dependent sets of coupling coefficients, based on what particular wavelength of light is incident on each of the PD elements.

[0033] In operation, optical power monitor **220** determines the actual incident power on each of PD elements **1**-N by measuring optical power at each PD element and applying a crosstalk matrix of coupling elements to solve the system of equations that expresses the measured optical power for all PD elements as a function of actual incident power on each PD element and the predetermined coupling coefficients. The predetermined coupling coefficients are found using method **400** and the system of equations is solved by constructing a crosstalk matrix of said coupling coefficients. Thus, application of the appropriate coupling coefficients eliminates the effect of crosstalk on the electrical outputs of PD array **250**.

[0034] FIG. **5** is a flow chart that summarizes, in a stepwise fashion, a method **500** for measuring optical power of light incident on PDs in a PD array, according to embodiments of the invention. Method **500** is described in terms of an optical power monitoring device substantially similar optical power monitor **220**, described above. However, other optical power monitoring devices may also benefit from the use of method **500**. Although the method steps are described in conjunction with FIG. **5**, persons skilled in the art will understand that any system configured to perform the method steps, in any order, falls within the scope of the present invention. Prior to the first step of method **500**, one or more sets of coupling coefficients are determined using method **400**. Multiple sets of coupling coefficients may be determined if the wavelength-dependence of crosstalk is assumed to be significant and if different wavelengths or wavelength bands are incident on different PD elements of PD array **250** during normal operation.

[0035] The method begins in step **501**, in which processor **270** measures electrical output **251** of each PD element of PD array **250**. It is noted that electrical output **251** of each PD element includes significant inaccuracy due to optical and electrical crosstalk from some or all of the other PD elements in PD array **250**.

[0036] In step **502**, processor **270** retrieves the appropriate coupling coefficients from memory block **303**. In embodiments in which different wavelengths or wavelength bands are incident on different PD elements, the coupling coefficients may be selectively retrieved from multiple coupling coefficient sets.

[0037] In step **503**, processor **270** solves the system of equations represented by Equation 3:

$$[P_{measured}]=[C][P_{incident}] \tag{3}$$

where $[P_{measured}]$ is the vector representing the electrical outputs **251** of PD elements **1**-N measured in step **501**, [C] is the crosstalk matrix constructed in step **502**, and $[P_{incident}]$ is the vector representing the actual incident power of light incident on each of the PD elements **1**-N.

[0038] In step **504**, processor **270** generates a corrected optical power value for each PD element based on the solution of Equation 3 for $[P_{incident}]$.

[0039] In sum, embodiments of the invention provide a PD array for measuring incident optical power and a method of accurately measuring optical power of light incident on each of the PDs in such an array. During operation, the effect of crosstalk between the individual PDs of the array is removed by measuring the current generated by each PD in the array and generating a corrected optical power value for each PD that is based on the measured current for each PD and on coupling coefficients associated with other PDs in the array. Thus, crosstalk can be greatly reduced in a PD array without modifying the structures of the PD elements.

[0040] While the foregoing is directed to embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

I claim:

1. A method of measuring optical power of light incident on photodiodes in a photodiode array, the method comprising:

measuring a current generated by a photodiode in the array in response to the light incident on the photodiode; and

generating an optical power value based on the measured current and correction factors associated with other photodiodes in the array.

2. The method of claim **1**, wherein the correction factors are coupling coefficients proportional to crosstalk between the photodiode and the other photodiodes.

3. The method of claim **1**, wherein a portion of the correction factors are coupling coefficients proportional to crosstalk between the photodiode and the other photodiodes when illuminated by a light in a first wavelength band and a remainder of the correction factors are coupling coefficients proportional to crosstalk between the photodiode and the other diodes when illuminated by light in a second wavelength band.

4. The method of claim **1**, wherein the correction factors are proportional to crosstalk between the photodiode and adjacent photodiodes.

5. The method of claim **1**, wherein the correction factors are coupling coefficients determined in a calibration procedure.

6. The method of claim **5**, wherein the calibration procedure comprises illuminating a single photodiode in the array with light and measuring the output of all photodiodes in the array.

7. The method of claim **1**, wherein generating an optical power value comprises constructing a crosstalk matrix with the correction factors.

8. The method of claim **7**, wherein generating an optical power value further comprises solving a system of linear equations using the crosstalk matrix.

9. The method of claim **1**, wherein the correction factors are coupling coefficients determined in a calibration procedure.

10. A computer-readable storage medium comprising instructions to be executed by a processing unit of an optical power monitoring device to carry out the steps of:

measuring a current generated by a photodiode in a photodiode array in response to the light incident on the photodiode; and

generating an optical power value based on the measured current and correction factors associated with other photodiodes in the array.

11. The computer-readable storage medium of claim **10**, wherein the correction factors are coupling coefficients proportional to crosstalk between the photodiode and the other photodiodes.

12. The computer-readable storage medium of claim **10**, wherein a portion of the correction factors are coupling coefficients proportional to crosstalk between the photodiode and the other photodiodes when illuminated by a light in a first wavelength band and a remainder of the correction factors are coupling coefficients proportional to crosstalk between the photodiode and the other diodes when illuminated by light in a second wavelength band.

13. The computer-readable storage medium of claim **10**, wherein the correction factors are proportional to crosstalk between the photodiode and adjacent photodiodes.

14. The computer-readable storage medium of claim **10**, wherein the correction factors are coupling coefficients determined in a calibration procedure.

15. The computer-readable storage medium of claim **14**, wherein the calibration procedure comprises illuminating a single photodiode in the array with light and measuring the output of all photodiodes in the array.

16. The computer-readable storage medium of claim **10**, wherein generating an optical power value comprises constructing a crosstalk matrix with the correction factors.

17. The computer-readable storage medium of claim **16**, wherein generating an optical power value further comprises solving a system of linear equations using the crosstalk matrix.

18. An optical power measuring system comprising:

a processor; and

a photodiode array,

wherein the processor is configured to perform the steps of:

measuring a current generated by a photodiode in the photodiode array in response to the light incident on the photodiode; and

generating an optical power value based on the measured current and correction factors associated with other photodiodes in the array.

19. The optical power measuring system of claim **18**, further comprising a memory unit configured to store instructions that, when executed by the processing unit, cause the processor to perform the steps of measuring and generating.

20. The optical power measuring system of claim **18**, wherein the correction factors are coupling coefficients proportional to crosstalk between the photodiode and the other photodiodes.

21. The optical power measuring system of claim **19**, wherein the processor is configured to perform the calibration procedure.

* * * * *