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Serial No.:
Inventors: Alan D. Kersey et al.

PATENT APPLICATION
Navy Case No. 77809

FIBER BRAGG GRATING INTERROGATION SYSTEM AND METHOD WITH FIBER STRING MULTIPLEXING

SPECIFICATION

1. Field of the Invention

The present invention relates generally to the field of fiber optic sensors and, more particularly, to addressing a large number of Bragg grating sensors.

2. Description of the Related Art

The basic prior art concept for addressing multiple Bragg gratings consists of a broadband source such as a light-emitting diode (LED), edge-emitting LED (ELED), or other superluminescent device illuminating a series of gratings along a fiber (a 'string' of gratings). When illuminated, each Bragg grating reflects a narrowband component of light at the Bragg wavelength, given by the expression:

$$\lambda_B = 2n\Lambda \qquad (1)$$

where Λ is the grating pitch and n is the effective index of the core. Perturbation of the grating, by temperature or strain, for example, results in a shift in the Bragg wavelength, which can be detected in the reflected spectrum. This shift can then be compared with the unperturbed Bragg wavelength to determine the extent of the perturbation.

One of the benefits of an FBG sensor lies in the fact that information is encoded into wavelength. This has a number of distinct advantages over other direct intensity based sensing schemes. Most importantly, wavelength is an absolute parameter. As a result, wavelength measurements are not affected by total light levels, losses in the connecting fibers and couplers, or source power.

Thus, fiber optic sensors based on the use of fiber Bragg grating (FBG) devices are useful in a variety of applications. They are particularly useful as embedded sensors for smart structures where the sensors can be used for real time evaluation of load, strain, temperature, vibration, and other variables. Since many gratings can be written into a length of fiber and addressed using multiplexing techniques, FBG sensors can provide quasi-distributed sensing capabilities.

The number of gratings which can be written into a single fiber, however, is limited by the bandwidth of the source illuminating the string. To map strain over large structural surfaces, it is necessary to address a large number of Bragg gratings -- more than one string of gratings typically contains. In light of the foregoing, there is a need for a wavelength determination system that can address large numbers of Bragg gratings.

Summary of the Invention

Accordingly, the present invention is directed to a system and method for addressing multiple strings of gratings using a single scanning filter. Such a system provides an efficient way to address large numbers of gratings and thereby cover a larger area than one string alone could.

Additional features and advantages of the invention will be set forth in the description which follows, and in part will be apparent from the description, or may be learned by practice of the invention. The objectives and other advantages of the invention will be realized and attained by the system and method particularly pointed out in the written description and claims hereof as well as the appended drawings.

To achieve these and other advantages and in accordance with the purpose of the invention, as embodied and broadly described, a system according to this invention includes a plurality of fiber strings, each string containing at least one grating, a coupler for directing spectral returns from the strings into a single scanning filter, and a processor for processing the light outputted by the filter to determine the wavelengths of the spectral returns.

In another aspect, a method according to this invention includes the steps of interrogating a plurality of grating strings, each string containing at least one grating, directing spectral returns from the gratings into a single scanning filter, and processing the light outputted by the filter to determine the wavelengths of the spectral returns.

Both the foregoing general description and the following detailed description are exemplary and explanatory and do not restrict the invention as claimed. The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the invention and, together with the description, explain the principles of the invention.

Brief Description of the Drawings

Fig. 1 is a schematic block diagram of an apparatus for addressing an FBG array;

Fig. 2(a) shows the optical return signal from the Bragg gratings of Fig. 1;

Fig. 2(b) shows the spectrum of the scanning optical filter of Fig. 1;

Fig. 2(c) shows the electrical signal present at the output of the photodetector of Fig. 1;

Fig. 2(d) shows the electrical signal present at the output of the derivative unit of Fig. 1;

Fig. 3 is a diagram of a derivative circuit;

Fig. 4 is a multiple array configuration utilizing a synchronously driven switch;

Fig. 5 is a multiple array configuration using synchronously driven sources;

Fig. 6 is a multiple array configuration using frequency intensity modulation; and

Fig. 7 is a multiple array configuration using code intensity modulation.

Description of the Preferred Embodiment

Reference will now be made in detail to the present preferred embodiment of the invention, an example of which is illustrated in the accompanying drawings. Where possible, like numerals are used to refer to like or similar components.

The exemplary embodiment of a wavelength determination system invention is shown in Fig. 1. As embodied herein and referring to Fig. 1, the wavelength determination system includes an edge-emitting light-emitting diode (ELED) 10, which transmits light through single mode optical fiber 15, through optical coupler 25, and into single mode optical fiber 16. A number of fiber Bragg gratings (FBGs) 20 are written into the optical fiber 16, in a manner well known in the art. These FBGs 20 will reflect specific optical wavelengths back through optical coupler 25 and into a tunable optical filter 30. The digital output from a digital, up/down counter 35 is converted to an analog voltage by a digital-to-analog (D/A) converter 40 and summed in a summing circuit 41 with a direct current (dc) offset voltage from an offset circuit 45 (to be discussed) to provide a signal to tune the tunable optical filter 30.

A photodetector 50 converts the optical output of tunable optical filter 30 into an electrical signal. A derivative unit 55 takes the derivative of this electrical signal and feeds it into zero-crossing detection circuitry 60. When zero-crossing detection circuitry 60 detects a zero-crossing, it sends an electrical signal to a latch 65 which captures the current value of up/down counter 35. A computer (PC) 70 stores and processes the latched value. A more detailed description of the invention will be given in connection with its operation.

In Fig. 1, ELED 10 transmits light into the optical fiber 16 which contains a plurality of fiber Bragg gratings (FBGs) 20. The FBGs 20 reflect certain wavelengths of light according to equation (1).

Fig. 2(a) depicts a typical set of return wavelengths for three FBGs 20 located along optical fiber 16. Optical coupler 25 directs the FBG return wavelengths into tunable passband optical filter 30, preferably a fiber Fabry-Perot (FP) filter. As is well known in the art, the passband of FP filters may be altered by electrically controlling the piezoelectric material creating the mirror spacing of the filter. The free spectral range of optical filter 30 must correspond to the range of possible reflected wavelengths from the FBGs 20. For example, using an array of 12 FBGs spaced by 3 nanometers (nm), the FP filter should have a free spectral range of around 45 nm.

A ramp waveform 42 controls the passband of optical filter 30. To generate ramp waveform 42, up/down counter 35 continuously counts from its lowest digital value to its highest, and back down. This digital signal is fed into D/A converter 40 which converts the signal to analog form, resulting in ramp waveform 42. Ramp waveform 42 controls the passband of optical filter 30 so that the filter 30 scans through the range of wavelengths reflected by the FBGs 20, an appropriate direct current (dc) voltage from offset circuit 45 is added to ramp waveform 42 to properly bias it.

Fig. 2(b) shows a typical passband of an FP filter, which scans through a wavelength spectrum.

As the passband of optical filter 30 sweeps through the spectral range, the FBG spectral returns are accordingly passed through optical filter 30 to photodetector 50. Photodetector 50 converts the FBG spectral returns into electrical signals, shown in Fig. 2(c). The peaks in this signal correspond to the reflected wavelengths from the FBGs 20. Therefore, it is necessary to precisely isolate the center of the peaks. The profile width of optical filter 30, however, limits the resolution of the photodetector signal. To improve the resolution, derivative unit 55 takes the derivative of the photodetector signal, resulting in the signal shown in Fig. 2(d). The derivative of the photodetector signal produces a zero-crossing t_{B1}, t_{B2}, and t_{B3} at each of the central wavelengths of the peaks in the photodetector signal.

The derivative of the signal may be performed in an analog circuit, a microprocessor or through the digital circuit shown in Fig. 3. In Fig. 3, the circuit 55' corresponds to derivative unit 55 in Fig. 1. The photodetector signal of Fig. 2(c) is passed to a fast analog to digital (A/D) converter 56 (such as the 16-bit Burr-Brown ADS7811) and then to a digital stack (RAM) 57, which serves to delay the measured value by a predetermined number of clock cycles N. A digital subtraction unit 58 then digitally subtracts the delayed photodetector signal from the direct signal to form an approximation of the signals shown in Fig. 2(d).

Zero-crossing detection circuitry 60 receives the output signal from derivative unit 55. When the voltage of the signal fed to zero-crossing detection circuitry 60 equals zero, the circuitry 60 activates latch 65. Latch 65 captures the current value of up/down counter 35, which corresponds to the wavelength optical filter 30 was tuned to when zero-crossing detection circuitry 60 detected a zero-crossing. This value can then be compared, in the exemplary computer 70, to the previously stored value associated with the unperturbed zero-crossing return wavelength. To ensure that zero-crossing detection circuitry 60 does not trigger latch 65 during spurious zero-crossings between actual FBG returns, the circuitry preferably contains a threshold detector (not shown). The threshold detector detects when the input signal rises above a predetermined level, shown by the dotted line 62 of Fig. 2(d), and signals to zero-crossing detection circuitry 60 that the next zero-crossing corresponds to a true FBG return.

To sum to this point, perturbations of the gratings alter the Bragg resonance conditions and change the wavelength of the reflected components. This results in shifts in the counter values at which zero-crossings occur that can then be translated into wavelength shifts representing the degree of perturbation. Using this approach, the central wavelength of several FBG sensors can be determined during each scan ramp cycle of the tunable FP filter. Scanning the filter at rates of several hundred hertz to potentially several kHz allows rapid updating of the FBG wavelengths. The use of an exemplary 16-bit up-down counter 35 for generation of the ramp signal provides a least significant bit resolution of less than 1 picometer (pm) for a filter with a free spectral range of less than 60 nanometers (nm). This wavelength resolution corresponds to a strain resolution of less than 1 μstrain at an operational wavelength of about 1.3 μm.

As discussed above, the bandwidth of the broadband source limits the number of sensors this system can address. A typical broadband source can address, for example, from 1 to 16 grating elements. By using the embodiments of the present invention, however, the scanning wavelength filter can be used to scan spectral returns from several strings of gratings where each string contains a number of grating elements. This increases the overall number of grating elements that a single scanning wavelength filter can address, allowing mapping of large structural surfaces.

The first embodiment, as illustrated in Fig. 4, uses an optical switch 75 (available from DiCon) that connects a single broadband source 10 and an optical filter 30 to a plurality of grating strings. Preferably, the computer 70 controls the optical switch 75 to sequentially interrogate each string. Wavelength determination block 80 corresponds to the combination of up/down counter 35, D/A converter 40, offset 45, latch 65, zero-crossing detection 60, and derivative unit 55 of Fig. 1.

The interrogation of each string proceeds in the manner described above. However, when the value of the up/down counter 35 for each string is latched into the computer 70, the computer 70 then associates the stored value with the corresponding position of the optical switch 75. In this way, the computer 70 can compare the spectral returns from each string with the previous returns from the same string. Thus, the addressing capability of the wavelength interrogation system increases manifold. For a sampling rate of approximately 1 kilohertz, the wavelength determination system can address 16 strings at approximately 60 hertz, a frequency adequate for many structural strain monitoring applications.

In a second embodiment, shown in Fig. 5, a plurality of broadband sources 10 each address a string of gratings. The computer 70 sequentially enables each of the broadband sources 10. A star coupler 85 combines returns from the strings allowing processing by a single scanning filter 30. Wavelength determination block 80 refers to the same components described with Fig. 4.

The interrogation of each string proceeds in the manner described above with Fig. 1. However, when the value of up/down counter 35 is latched into the computer 70, the computer 70 then associates the stored value with the corresponding enabled broadband source 10. In this way, the computer 70 can compare the spectral returns from each string with previous returns from the same string.

In a third embodiment, shown in Figs. 6 and 7, a plurality of broadband sources 10 each illuminate a string of Bragg grating sensors. As in the second embodiment, a star coupler 85 combines the spectral returns from the strings allowing processing by a single scanning filter 30. However, unlike the second embodiment, each of the sources 10 runs continuous-wave (CW). In order to differentiate among the spectral returns, the sources are intensity-modulated. This can be done, for example, with frequency or code modulation. In the former case, shown in Fig. 6, the sources are modulated at different frequencies with the frequency components synchronously detected at the photodetector 50 output. In the latter, shown in Fig. 7, a code such as an m-sequence or Gold code is applied to each source. Correlation detection at the photodetector 50 output separates outputs from each grating string.

It will be apparent to those skilled in the art that various modifications and variations can be made in the present invention without departing from the spirit or scope of the invention. For example, a variety of narrowband filters can be used, including fiber coupled Fabry-Perot interferometers, cascaded Mach Zehnders, acousto-optically tuned filters, polarization based filters and in-fiber grating based filters.

It is intended that the present invention cover the modifications and variations of this invention.

Serial No.:
Inventors: Alan D. Kersey et al.

PATENT APPLICATION
Navy Case No. 77809

Abstract

A wavelength determination system and method for addressing a plurality of strings of Bragg grating sensors using a single digitally controlled narrowband optical filter.

Navy Case No. 77,809

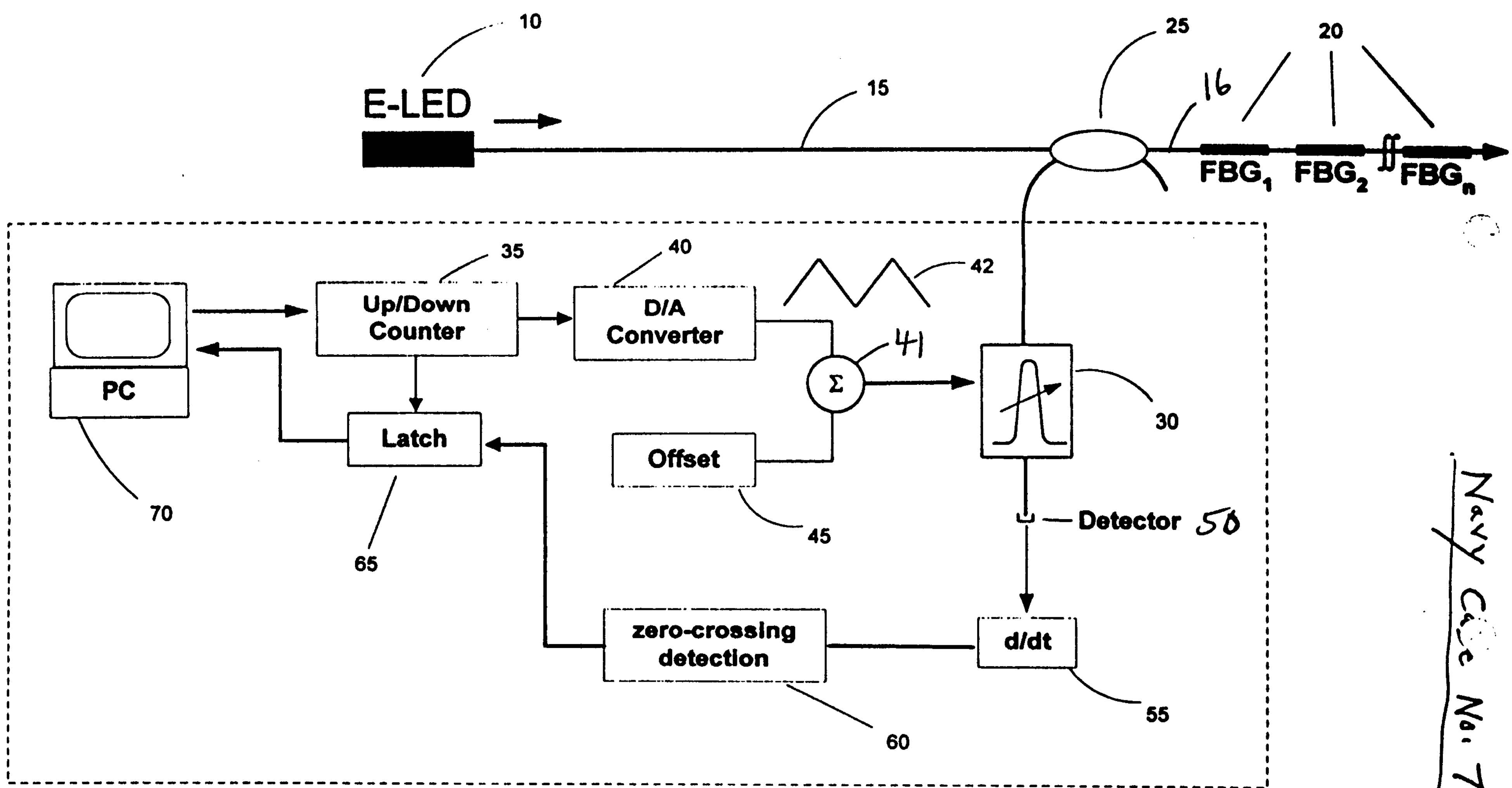


Fig. 1

Fig. 2(a)

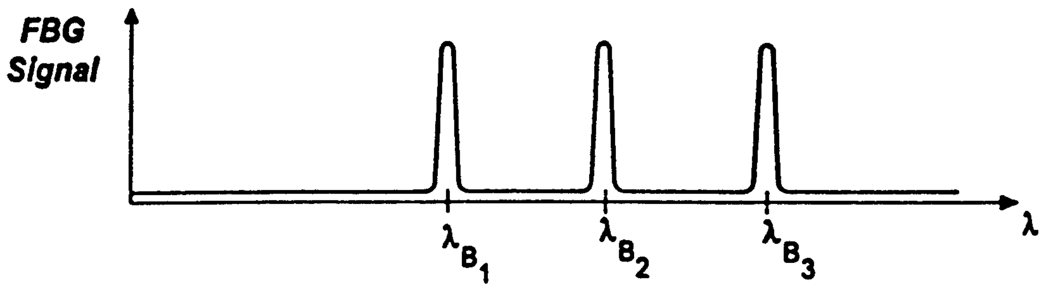


Fig. 2(b)

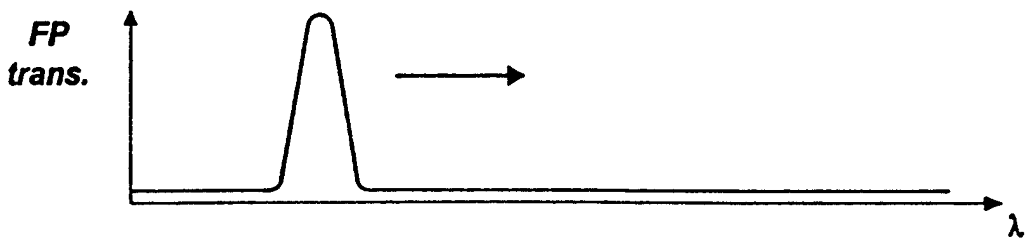


Fig. 2(c)

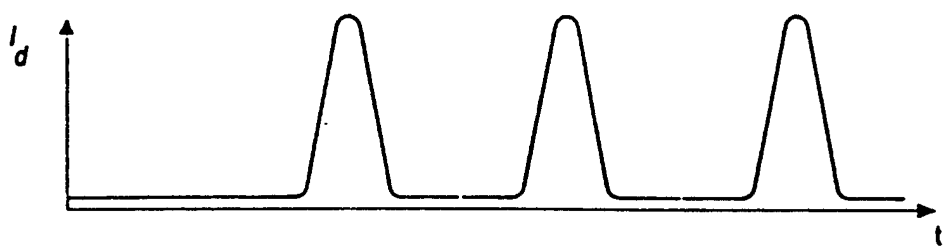
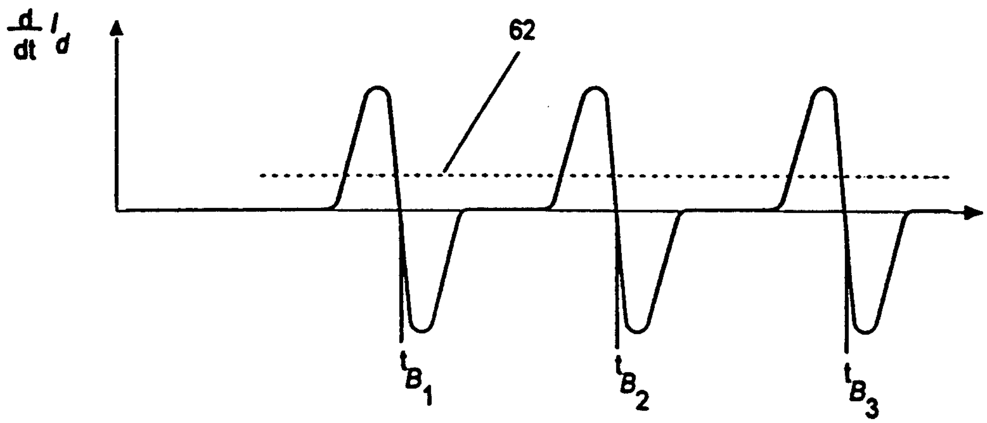
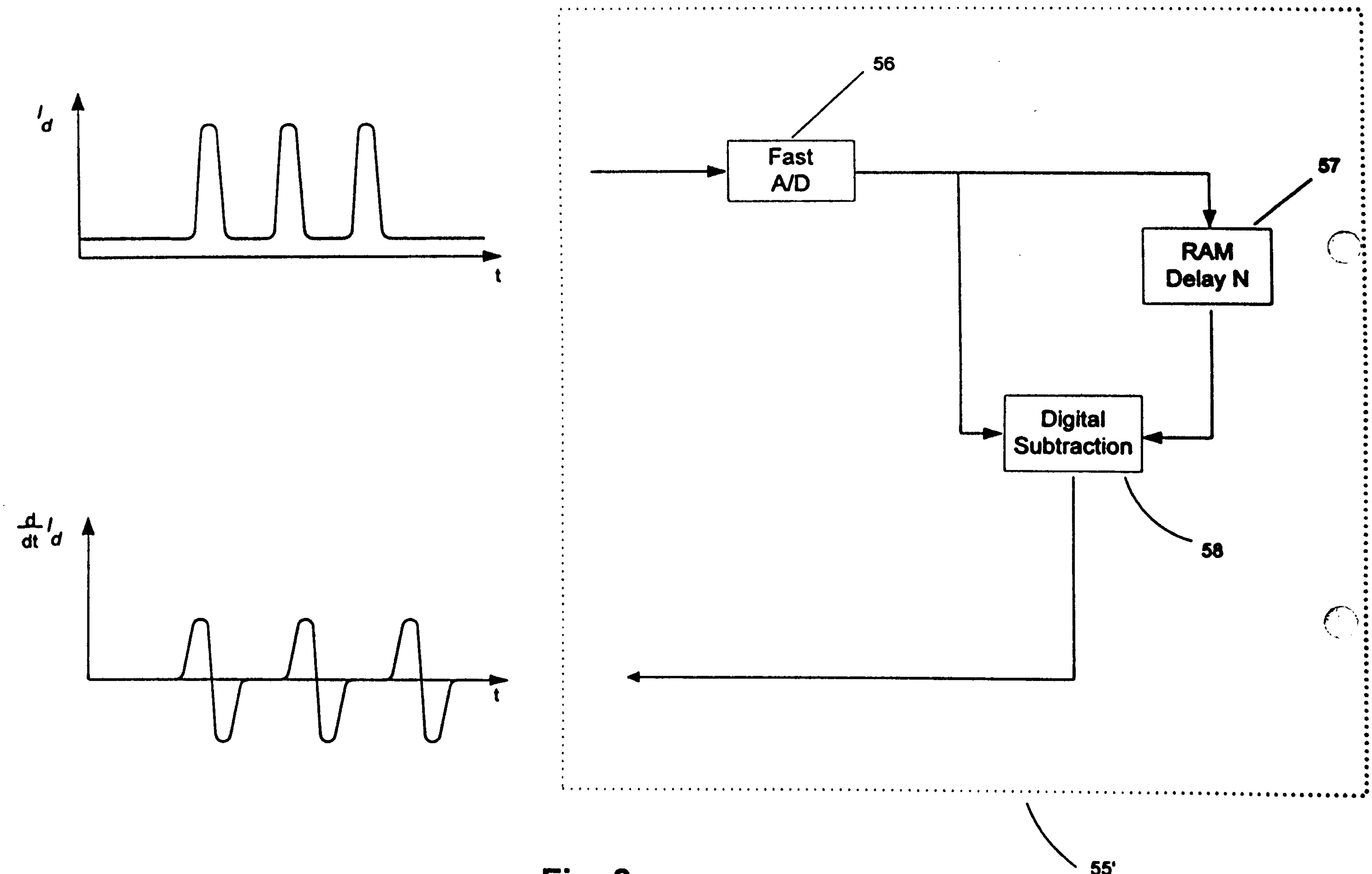


Fig. 2(d)





I_d
t
$\frac{d}{dt} I_d$
t
Fast
A/D
56
RAM
Delay N
57
Digital
Subtraction
58
55'

Fig. 3

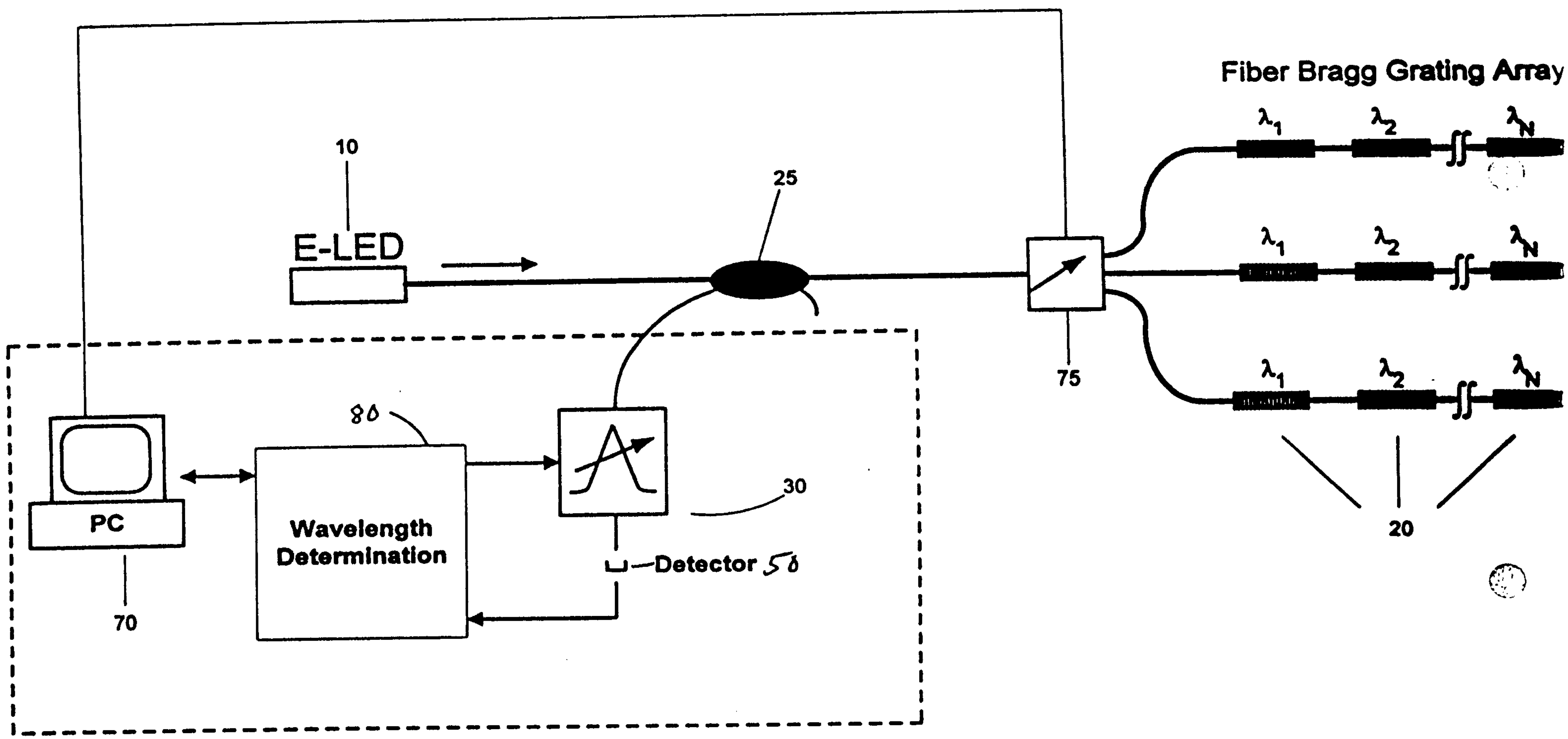
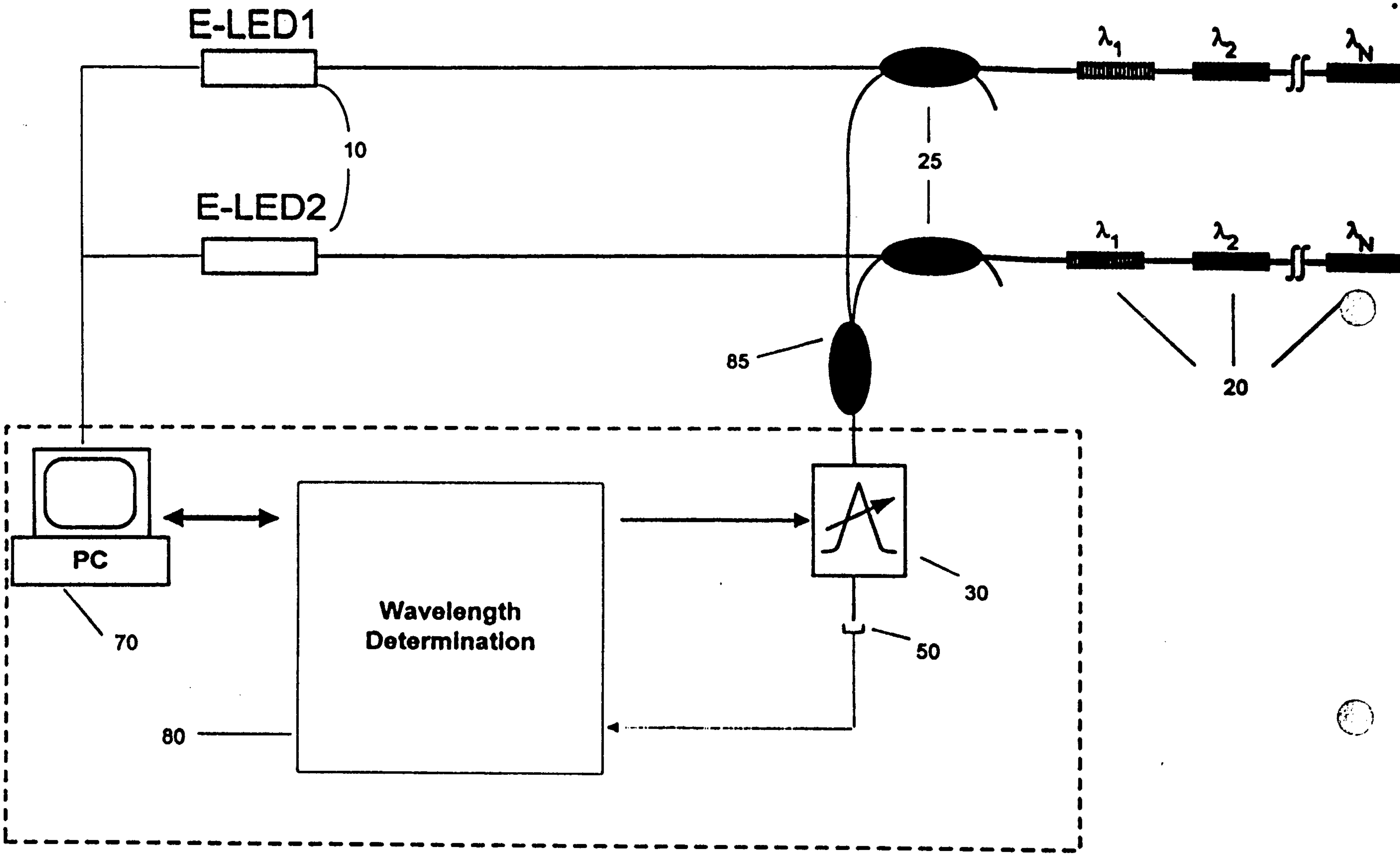
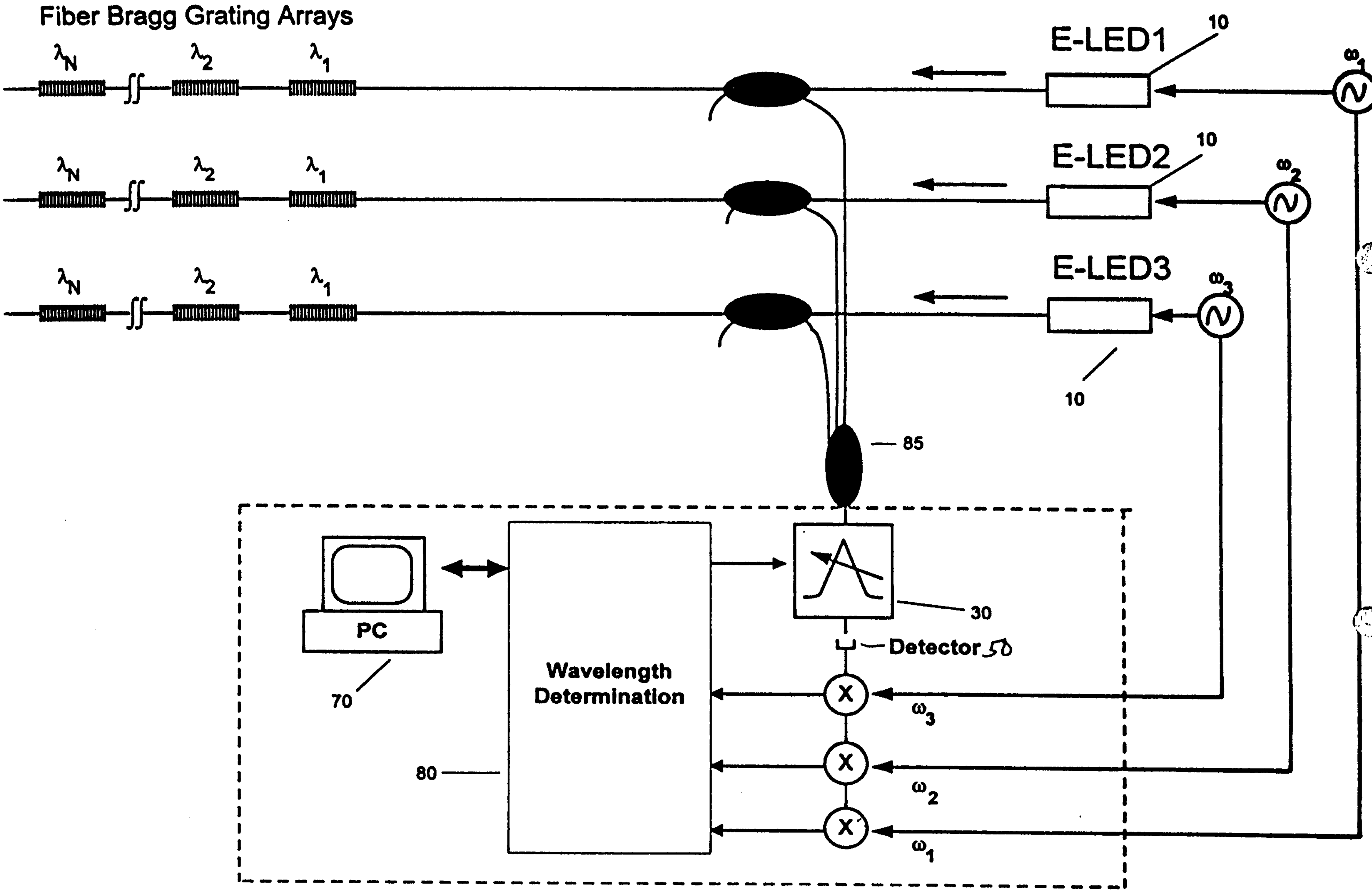

Fiber Bragg Grating Array
λ_1
λ_2
λ_N
20
75
25
10
E-LED
80
PC
70
Wavelength Determination
30
Detector 50

Fig. 4

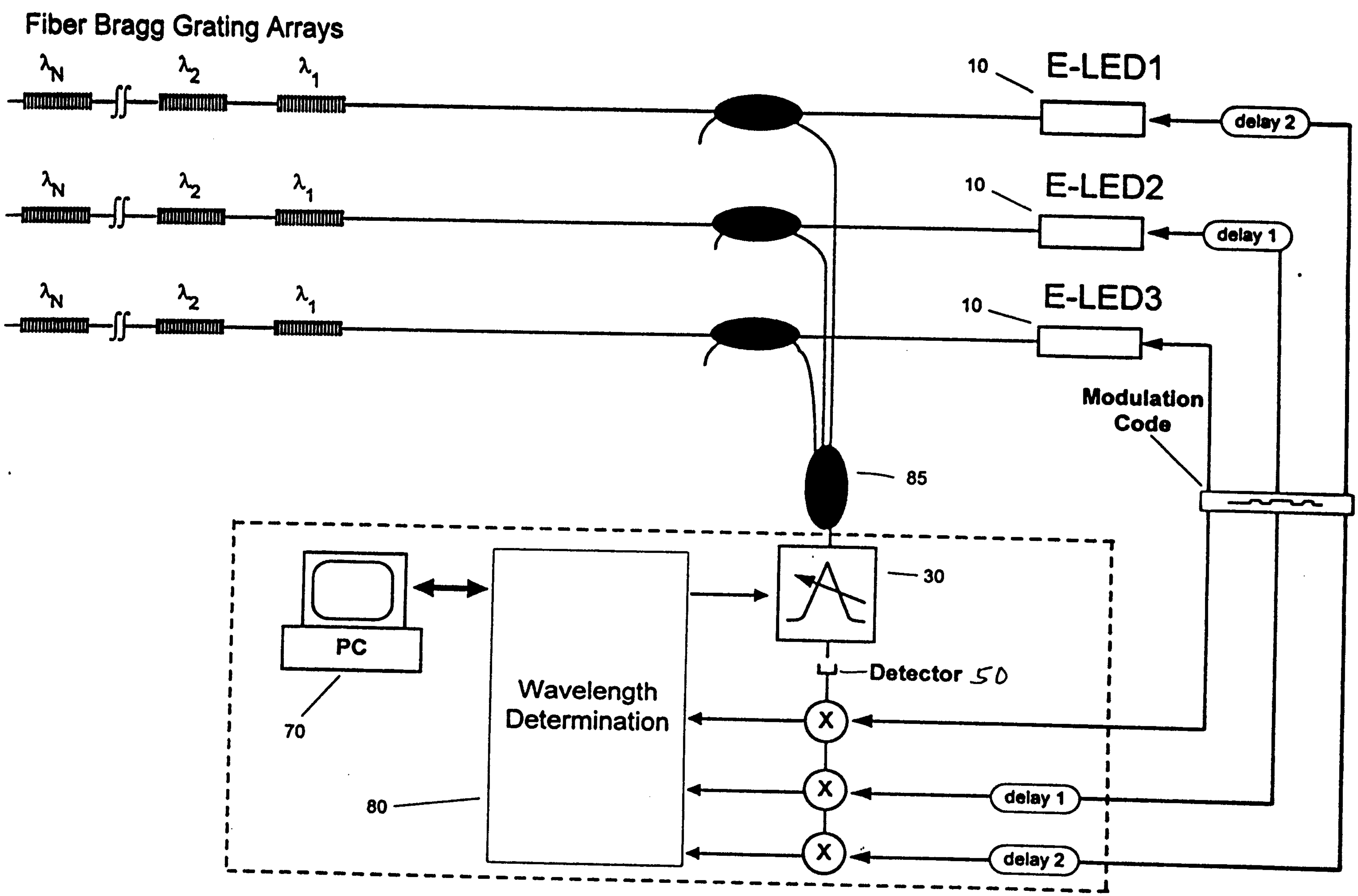


E-LED1
E-LED2
10
25
λ_1
λ_2
λ_N
λ_1
λ_2
λ_N
85
20
PC
70
Wavelength
Determination
80
30
50

Fig. 5



Fiber Bragg Grating Arrays
λ_N
λ_2
λ_1
E-LED1
E-LED2
E-LED3
10
ω_1
ω_2
ω_3
85
30
Detector 50
PC
70
Wavelength Determination
80
X



Fiber Bragg Grating Arrays
λ_N
λ_2
λ_1
λ_N
λ_2
λ_1
λ_N
λ_2
λ_1
10
E-LED1
10
E-LED2
10
E-LED3
delay 2
delay 1
Modulation Code
85
30
PC
Wavelength Determination
Detector 50
70
80
delay 1
delay 2

Fig. 7