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WASHINGTON DC 20375

Inventors: Carruthers et al.
Serial No.

PATENT APPLICATION
Navy Case No. 79,766

ULTRASHORT-PULSE FIBER LASER WITH A DISPERSION-MANAGED CAVITY

BACKGROUND OF THE INVENTION

Field of the Invention

This invention in general refers to dispersion management within a laser cavity and more particularly to a laser apparatus where dispersion management is used to enhance the performance of the laser by reducing the timing jitter of the pulses produced by the laser and by reducing the occurrence of pulse dropouts or multiple pulse production.

Description of the Related Art

Dispersion management within a laser cavity allows a fiber laser to produce optical pulses of lower amplitude and phase noise and with greater immunity to pulse dropouts than is otherwise possible. These features are of great importance to lasers used as sources in telecommunications applications, as research instruments, or in optical-to-digital conversion and analysis application.

Dispersion management is a concept usually encountered only in optical soliton fiber transmission applications. In that field, it has been found that the use of lengths of at least two types of fibers with different chromatic dispersions, usually of differing signs, but with a (usually small) net anomalous dispersion, yields a transmission medium with distinct advantages over one with a uniform dispersion: i) the optical energy of the solitons carrying information is greater than those in a uniform-dispersion fiber with the net dispersion, yielding a greater signal-to-noise (S/N) ratio of the signal; ii) the timing jitter in the system is lower; iii) the pulses tend to have a Gaussian temporal profile, reducing pulse-to-pulse interactions; iv) nonlinear pulse interactions such as four-wave mixing are strongly reduced because of the strong local dispersion. The strength of dispersion management is usually expressed as a unitless parameter

$$\gamma = 2\sum_n \left|\beta''_n \ell_n\right| \Big/ \tau^2$$

where β''_n and ℓ_n are the dispersion and length respectively, of fiber segment n, and τ is the pulse duration.

Dispersion-managed solitons have two salient properties for the purposes herein: their energy is greater than that of an equivalent uniform-dispersion soliton, and their pulse duration changes much less with a change in pulse energy than does an equivalent uniform-dispersion soliton.

In an actively harmoncally mode-locked soliton laser four regimes of operation are expected to be seen as the amount of energy per pulse is varied: (i) At the lowest energies, the laser cannot form solitons, and a very noisy output of long-duration pulses is evident. (ii) At somewhat higher energies, there is not enough power available for a full train of solitons, so the laser can form either a train of long-duration pulses or an occasional soliton. The laser loss is higher for long-duration pulses, since they would be clipped by the finite duration of the amplitude mode-locking time window. Therefore a combination of solitons and dropouts is observed. (iii) At higher frequencies, the laser can produce an uninterrupted stream of solitons. In this regime, the pulse duration becomes briefer as the pulse energy increases. (iv) At the highest energies, pulses are prevented from becoming more brief by the fact that energy is lost when they become so brief and their bandwidth consequently becomes so large that the pulses are clipped spectrally by the finite gain bandwidth (or the bandwidth of an intracavity bandpass filter). Then multiple pulses begin to appear in each time slot.

The desirable operating regime from a telecommunications standpoint is (iii), in which an uninterrupted stream of pulses is generated. The maximum and minimum pulse widths which define the boundaries of this regime are determined by the details of the laser parameters.

In a laser of uniform dispersion, the pulse energy range over which the laser operates in the stable regime can be as small as 30%. One characteristic of a dispersion-managed laser is that the pulse duration decreases by comparatively little as the pulse energy increases; as a consequence, the laser can operate in the stable regime over a pulse energy range of as much as a factor of 100.

BRIEF SUMMARY OF THE INVENTION

The object of this invention is to provide a dispersion-managed soliton laser exhibiting a greater immunity to pulse dropouts than an equivalent uniform-dispersion soliton laser along with lower amplitude noise and timing jitter.

Another objective of this invention is to produce a soliton fiber laser that can produce pulses with adjustable temporal and spectral intensity profiles and durations to suit particular applications.

These and other objectives are attained by ultrashort fiber laser with a dispersion-managed cavity. The laser is an actively mode-locked sigma laser, typically locked at a repetition rate of 10 GHz, driven by an external frequency source and actively length stabilized, and nearly 10,000 pulses circulate within the laser cavity. A Mach-Zehnder modulator is placed in a loop of polarization-maintaining (PM) fiber. The polarization state of light injected into the non-PM branch evolves in a random manner but is transformed into an orthogonal state by a Faraday mirror; linearly polarized light injected into the branch by a polarizing beamsplitter returns to the beamsplitter also linearly polarized but rotated by 90°. The cavity of the laser is composed of several fibers. The average dispersion D_{av} is anomalous and is approximately equal to 2 ps/(nm·km). The measured noise in the output of the laser is very low, the rms amplitude noise is less than 1.1% and the rms timing jitter is less than 160 femtoseconds.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1a shows a basic schematic of a dispersion-managed, actively mode-locked, all polarization-maintaining fiber laser.

Figure 1b shows a basic schematic of a dispersion-managed, actively mode-locked, all polarization-maintaining fiber laser containing an optical bandpass filter.

Figure 1c shows a basic schematic of a dispersion-managed, actively mode-locked, all polarization-maintaining fiber laser containing an optical isolator.

Figure 1d shows a basic schematic of a dispersion-managed, actively mode-locked, all polarization-maintaining fiber laser containing a PZT cylinder-based length-stabilizing system.

Figure 1e shows a basic schematic of a dispersion-managed, actively mode-locked, all polarization-maintaining fiber laser containing a air gap-based length-stabilization system.

Figure 2a shows an ultrashort-pulse dispersion-managed soliton sigma fiber laser with the optical modulator in the polarization-maintaining branch.

Figure 2b shows an ultrashort-pulse dispersion-managed soliton sigma fiber laser with the optical modulator in the birefringence-compensating branch.

Figure 2c shows a regeneratively-locked laser without length-stabilization.

Figure 2c shows a regeneratively-locked laser with length-stabilization.

Figure 3a shows an infinite-persistence oscilloscope trace of the lowest optical powers of the detected optical pulses of a duration of ~5 ps on the left and an autocorrelation trace on the right the three regimes of operation as the amount of energy per pulse is varied.

Figure 3b shows an infinite-persistence oscilloscope trace of the lowest boundary of Regime II, showing the pulse dropouts whose number decreases from lower to higher powers, and pulse durations between 2.6 and 3.3 ps.

Figure 3c shows an infinite-persistence oscilloscope trace of the upper boundary of regime II, showing the pulse dropouts whose number decreases from lower to higher powers, and pulse durations between 2.6 and 3.3 ps.

Figure 3d shows an infinite-persistence oscilloscope trace of the lower boundary of regime III, showing filled pulse trains and pulse durations between 1.4 and 3.3 ps.

Figure 3e shows an infinite-persistence oscilloscope trace of the highest experimental power, showing filled pulse trains and pulse durations between 1.4 and 3.3 ps.

Figure 4 shows a plot of the bit-error rate in a data transmission experiment using the dispersion-managed soliton sigma laser.

Figure 5a shows the temporal characteristics of the output pulses.

Figure 5b shows the spectral characteristics of the output pulses.

Figure 6a shows a basic dispersion-managed, actively mode-locked, partially polarization-maintaining fiber, partially non-polarization-maintaining fiber laser with a polarization controller.

Figure 6b shows a basic dispersion-managed, actively mode-locked, non-polarization-maintaining fiber laser wwith a polarization controller.

Figure 6c shows a basic dispersion-managed, actively mode-locked, partially polarization-maintaining, partially non-polarization-maintaining fiber laser containing an optical isolator, a birefringence-compensating branch, a polarizing beamsplitter, an optical bandpass filter, and a Faraday mirror.

DETAILED DESCRIPTION OF THE INVENTION

In a first preferred embodiment a basic mode-locked pulse dispersion-managed soliton sigma laser **10**, as shown in **Figure 1a**, comprises a dispersion-managed cavity **11** having at normal dispersion medium **13** and a anomalous-dispersion medium **15**. The normal dispersion medium **13** and the anomalous-dispersion medium **15** has oppposite4 signs of chromatic dispersion for stretching the pulse width and lower the peak power of the optical pulse. An optical signal within a loop **21** is modulated by applying a signal from a periodic drive **12** applied to a modulator by an optical modulator **14**, and amplified by an optical amplifier **17**, An optical coupler **19** removes the optical signal from the loop and applies it to other processing elements (not shown). The periodic drive **12** may be an external frequency source such as a master clock (synthesizer). The loop **21** is, preferably, a polarization-maintaining optical fiber.

In a second embodiment of a basic dispersion-managed, actively mode-locked, all polarization-maintaining fiber laser **20**, as shown in **Figure 1b**, the same optical circuit is utilized, as that shown in **Figure 1a**, however an optical tunable or variable bandpass filter **24** is inserted into the loop **21** prior to the modulator **14** to pass a select band of optical frequencies.

In another embodiment of a basic dispersion-managed, actively mode-locked, all polarization-maintaining fiber laser **30**, as shown in **Figure 1c**, the same optical circuit is utilized, as that shown in **Figure 1a**, however an optical isolator **46** is inserted into the loop **21** prior to the modulator **14** to ensure unidirectional flow of optical light.

In another embodiment of a basic dispersion-managed, actively mode-locked, all polarization-maintaining fiber laser **40**, as shown in **Figure 1d**, the same optical circuit is utilized, as that shown in **Figure 1a**, however an optical fiber wound on a PZT cylinder **27** with length-stabilizing electronics **28** controls the length of the optical fiber

In another embodiment of a basic dispersion-managed, actively mode-locked, all polarization-maintaining fiber laser **60**, as shown in **Figure 1e**, the same optical circuit is utilized, as that shown in **Figure 1a**, however an adjustable air gap **48** with length-stabilizing electronics **28** controls the length of the optical fiber

In a second preferred embodiment of the ultrashort-pulse fiber laser, as shown in **Figure 2a**, the laser **70** is an actively mode-locked sigma laser, driven by an external frequency source, or master clock (synthesizer) **12** and actively length-stabilized. An optical modulator **14**, such as a Mach-Zehnder modulator, is placed in a loop **21** of polarization-maintaining (PM) fiber forming a polarization-maintaining loop. To ensure unidirectional operation, an optical isolator **23** is contained within the laser cavity. The polarization state of light injected into the birefringence-compensating section or banch **18** evolves in a random manner but is transformed into an orthogonal state by a Faraday mirror **22**; linearly polarized light injected into the birefringent-compensating branch **18** by the polarizing beamsplitter **24** returns to the beamsplitter **24** also linearly polarized but rotated by 90°. An optical circulator may be used in place of a polarizing beamsplitter **24** if so desired. An oiptical gain medium within the laser cavity amplifies the intensity of light circulating in the cavity. The linearly polarized light injected into the birefringence-compensating branch **18** passes through a section of optical fiber wrapped around a piezo electric cylinder **27** forming a laser cavity whose length is controlled by the application of an electrical signal from length-stabilization electronics **28**. The means for controlling the length of the laser cavity may also be through the use of an adjustable air gap.

In another preferred embodiment **80**, **Figure 2b**, the optical modulator **14** may be placed elsewhere in the cavity, such as in the birefringent-compensating branch **18**, adjacent to the Faraday mirror **22**. The modulator **14** should be very close to the end of the birefringent-compensating branch **18** since it must be "open" both for incident and returning light.

The cavity of the laser **70** is composed of several fibers, which types, lengths, and locations are set forth in **Table 1**. The average dispersion D_{av} is anomalous and is approximately equal to 0.1 ps/(nm·km); the total cavity is typically ~ 195 m.

The lasers **70**, **80**, and **90** are mode-locked at a repetition rate of, preferably, 10 GHz, by driving the modulator **14** with an external periodic drive **12** at 10 GHz which is an integral of the fundamental cavity frequency. Within the laser cavity there are nearly 10,000 pulses circulating and it is usually difficult to attain a uniform stream of uninterrupted pulses in an actively mode-locked laser with such a high harmonic order.

In another preferred embodiment **90** as shown on **Figure 2c**, a regenerative mode-locked device us shown. An optional soliton propagation fiber **32** is placed in the optical circuit prior to the Faraday mirror **22**. The optical signal is modulated in a modulator **14** with an electrical signal that is the product of a regenerative cycle. The regenerative cycle is comprised of removing an optical signal from the loop by the use of a pair of optical couplers **19** and **33**, converting the optical signal to an electrical signal in a photodetector **38**, removing any unwanted frequencies in a bandpass filter **36**, adjusting the phase **37**, amplifying the phase adjusted electrical signal, amplifying it and applying it to the optical signal in the loop in a modulator **14.**

In another preferred embodiment **100**, as shown on **Figure 2d**, a regenerative mode-locked device with length-stabilization is shown. The optical signal is modulated by a regenerative electrical signal similar to that shown in **Figure 2c**, however, a electrical signal from after a bandpass filter **36** is applied after phase adjustment **42** to the length stabilization electronic circuit **28** to control an optically wound PZT cylinders **27** diameter, similar to that described for **Figure 2a.**

The lasers **70**, **80**, **90**, and **100** exhibit a measured pulse dropout rates below 10^{-14}. The measured noise in the output **26** of the lasers **70**, **80**, **90**, and **100** are also very low: the rms amplitude noise is less than 1.1% and the rms timing jitter is less than 160 femtoseconds.

In the subject invention, three regimes are predicted, **See Figures 3a** through **3e**, and show long-duration sampling oscilloscope pulse traces, on the left, paired with the pulse autocorrelation, on the right, for a series of average pulse powers expressed as a fraction of the maximum pulse power P_{max}. The Roman numerals signify the three observed regimes of operation of the laser. The highest energy regime cannot be obtained with the optical amplifier powers available, however, modeling shows that stable operation may be obtained over a range of pulse energies of at least a factor of three.

TABLE 1

Fiber Type	Location	Length(m)	Dispersion D (ps/[nm· km])*
Polarization-maintaining (PM)	PM Loop	15	~17
SMF-28	Birefringence-compensating branch	10†	~17
Dispersion-shifted (DSF)	"	55†	~10
Dispersion-compensating (DCF)	"	15†	- 65
Gain fiber (EFA)	"	10†	~8

It is evident in **Figures 3a** through **3e** that the amplitude noise of the laser output decreases as the pulse energy is increased; the same is true for the timing jitter. The decrease in noise levels as pulse energy is increased is also a consequence of dispersion-management: a dispersion-managed soliton has a higher energy than an equivalent uniform-dispersion soliton, and the noise-inducing effects of amplified spontaneous emission in the fiber amplifier are therefore minimized.

Figure 4 is a plot of the bit-error rate in a data transmission experiment using the dispersion-management soliton sigma laser, demonstrating that its pulse dropout ratio is as low as 10^{-14}. These back-to-back bit-error ratio measurements were made at 10Gb/s using the solitan sigma laser as a source.

Figures 5a and **5b** show the temporal and spectral characteristics of the output pulses; pulse duration is 1.1 picoseconds generated with the dispersion-managed soliton laser, the autocorrelation, on the left, and optical spectrum, on the right. The pulse is approximately Gaussian in temporal shape.

A dispersion-managed soliton laser exhibits a greater immunity to pulse dropouts than an equivalent uniform-dispersion soliton laser and exhibits lower amplitude noise and timing jitter. Also, a dispersion-managed soliton fiber laser can produce pulses with adjustable temporal and spectral intensity profiles and durations to suit particular applications.

The critical factor in the dispersion-managed soliton fiber laser is the existence of a dispersion map in the laser cavity; other construction details of the laser may vary.

(i) A passively mode-locked dispersion-managed laser should exhibit superior characteristics to an equivalent uniform-managed soliton laser -- its amplitude noise and timing jitter should be lower.

(ii) An actively mode-locked laser can be either amplitude- or phase-modulated using any of a number of modulator types.

(iii) An actively mode-locked laser can be mode locked by an external frequency standard and length-stabilized by a number of means, such as electronic circuits; such stabilization techniques are well known to those skilled in the art,.

(iv) An actively mode-locked laser can be regeneratively mode-locked.

(v) A dispersion-managed laser can have more or all types of its fibers compose of PM fiber, so that fewer fibers need be placed in the birefringence-compensating branch; if all fiber types are polarization-maintaining, the birefringence-compensating branch is not needed.

(vi) Although it is preferred if the dispeersion-managed laser cavity be partially polarization-maintaining and birefringent-compensating, as in **Figures 2a** and **2b,** it may also be partialy polarization-maintaining and partially non-polarization-maintaining, as shown in **Figure 6a** and **6c**, non-polarization-maintaining, as shown in **Figure 6b**, or totally polarization-maintaining, as shown in **Figure 1a**.

(vii) A dispersion-managed laser can have several of its component fibers serving more than one purpose. For instance, the optical gain fiber might be designed to have a large normal dispersion, eliminating the need for a separate dispersion-compensating fiber.

(viii) Normal-dispersion fiber might not be necessary in a dispersion-managed laser. Component fibers that possess anomalous dispersion but of differing magnitudes may be used and some or all of the advantages of dispersion management may be retained.

(ix) Dispersion of either sign need not be provided by lengths of fiber. For instance, fiber Bragg gratings can add either type of dispersion to the laser cavity; so can fiber-integrated diffraction gratings, prisms, photonic bandgap materials, or bulk dispersive material.

(x) For ensuring that the periodic drive is an integral multiple of the fundamental frequency a PZT cylinder is preferred, however, an air gap may be used, as shown in **Figure 1e**. Or,the frequency of the periodic drive may be varied to match the integral multiple fundamental cavity frequency by the use of a voltage control oscillator or regenerative locking, as in **Figures 2c** and **2d**.

(xi) The modulator may be an optical modulator, such as a Mach-Zehnder modulator, wherein it is modulated with an electrical signal, or it may be of another type, such as a light-by-light modulator wherein the optical signal is modul;ated by another optical signal.

(xii) A polarization controller **62** may be used, as in **Figures 6a** and **6b** to control the phase of the optical signal.

This above-described invention differ from what is taught in the Statutory Invention Registration (SIR) by Carruthers et al., entitled PICOSECOND-TO-FEMTOSECOND ERBUIM FIBER LASER, Serial No. 08/825,942, filed on April 1, 1997; in that the dispersion map has close to optimum strength so that the average dispersion is much closer to zero than that taught in the SIR. The device taught in the SIR does not have a dispersion map *per se*; the purpose of the dispersion-compensating fiber in the SIR is merely to reduce the average dispersion of the laser to a manageable level.

Although the invention has been described in relation to an exemplary embodiment thereof, it will be understood by those skilled in the art that still other variations and modifications can be affected in the preferred embodiment without detracting from the scope and spirit of the invention as described in the claims, as can be seen in the various figures.

Inventors: Carruthers et al.
Serial No.

PATENT APPLICATION
Navy Case No. 79,766

ABSTRACT

The ultrashort fiber laser with a dispersion-managed cavity. The laser is an actively mode-locked sigma laser, typically locked at a repetition rate of 10 GHz, driven by an external frequency source and actively length stabilized, and nearly 10,000 pulses circulate within the laser cavity. A Mach-Zehnder modulator is placed in a loop of polarization-maintaining (PM) fiber. The polarization state of light injected into the non-PM branch evolves in a random manner but is transformed into an orthogonal state by a Faraday mirror; linearly polarized light injected into the branch by a polarizing beamsplitter returns to the beamsplitter also linearly polarized but rotated by 90°. The cavity of the laser is composed of several fibers. The average dispersion D_{av} is anomalous and is approximately equal to 0.1 ps/(nm·km). The measured noise in the output of the laser is very low; the rms amplitude noise is less than 0.1 percent over a frequency range of 10 Hz - 1 MHz, and the rms timing filter is less than 10 femtoseconds over a frequency range of 100 Hz - 1 MHz.

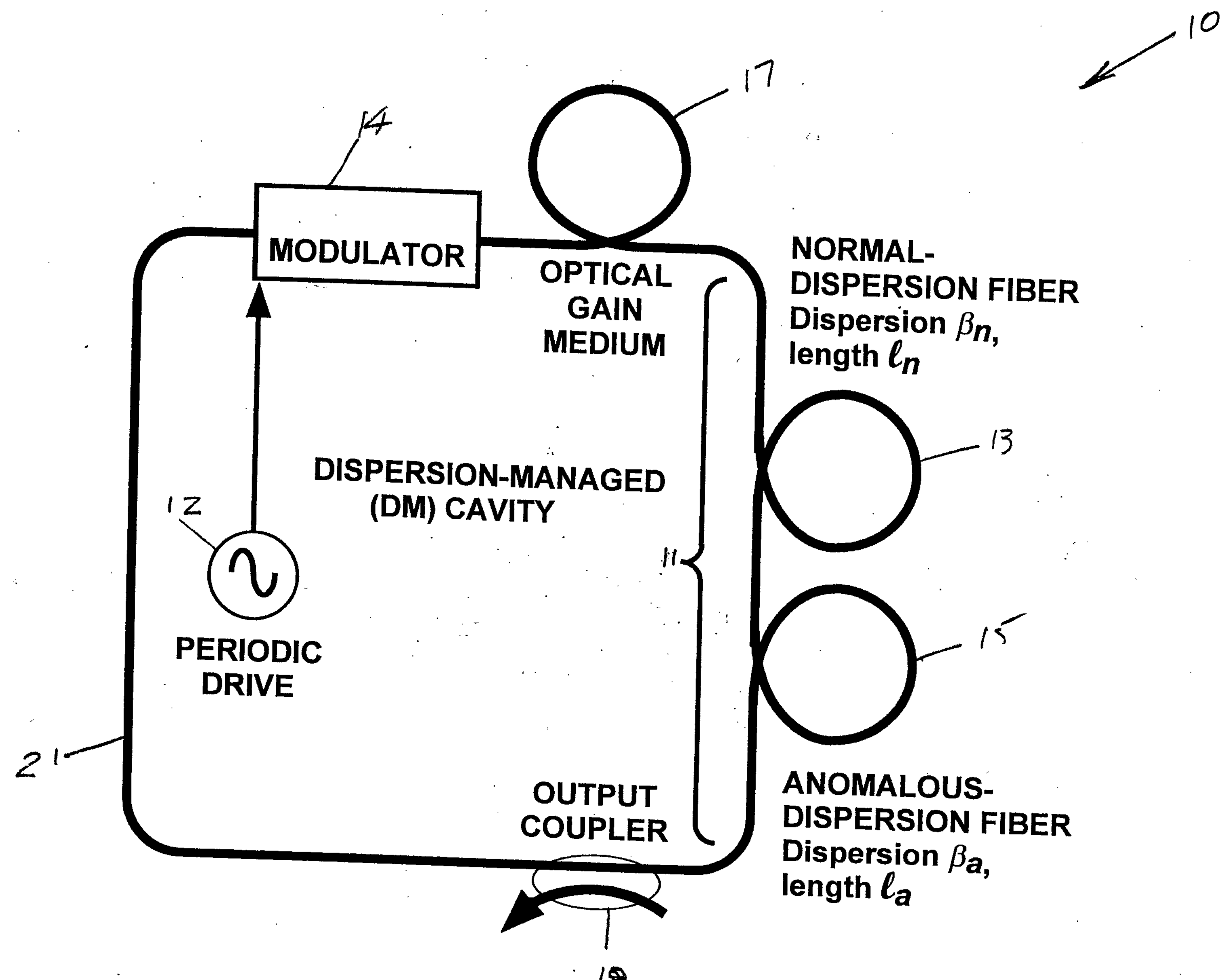

10
17
14
MODULATOR
OPTICAL
GAIN
MEDIUM
NORMAL-
DISPERSION FIBER
Dispersion β_n,
length ℓ_n
13
DISPERSION-MANAGED
(DM) CAVITY
12
11
15
PERIODIC
DRIVE
21
OUTPUT
COUPLER
ANOMALOUS-
DISPERSION FIBER
Dispersion β_a,
length ℓ_a
19

Figure 1a

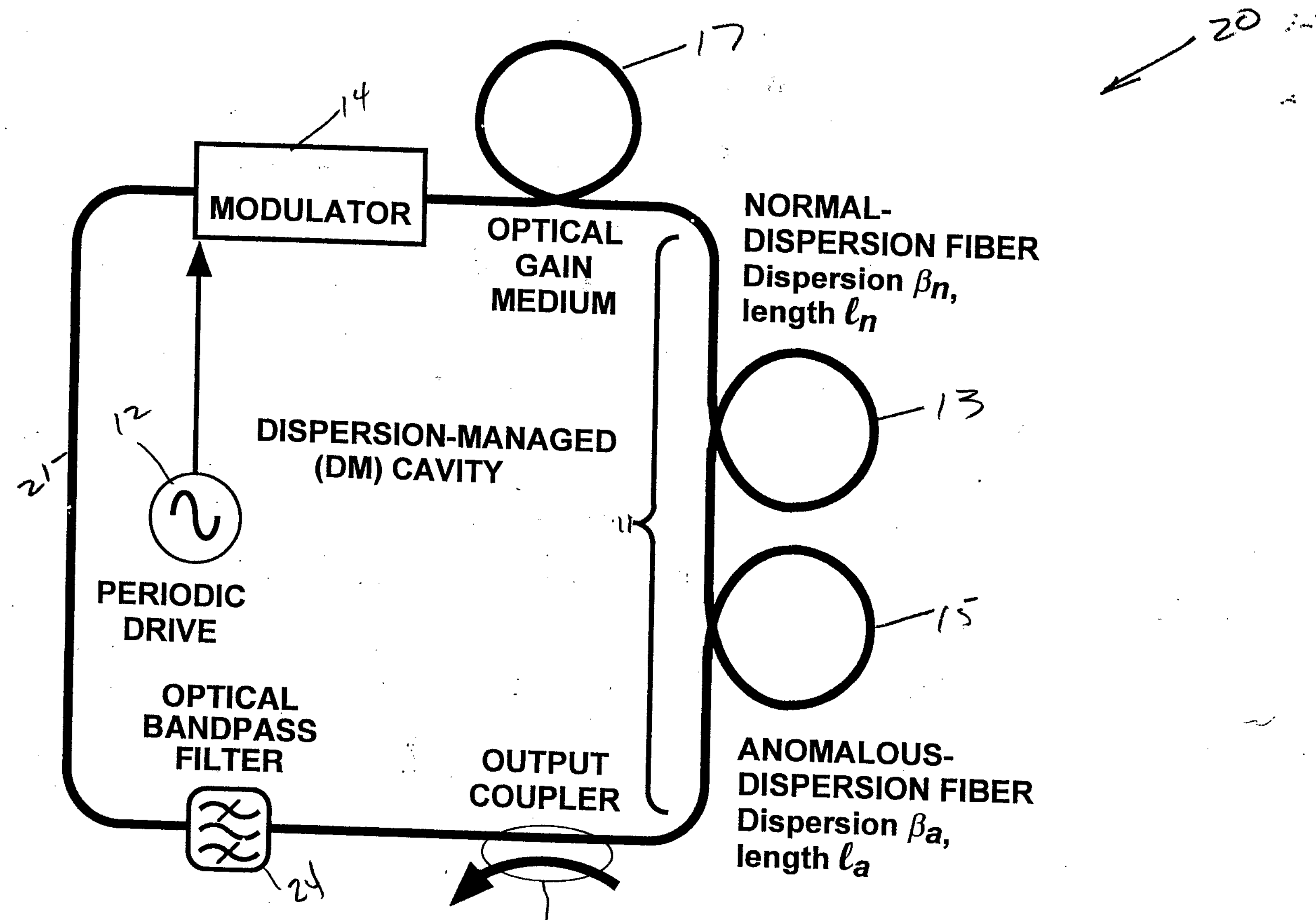

20
17
14
MODULATOR
OPTICAL
GAIN
MEDIUM
NORMAL-
DISPERSION FIBER
Dispersion β_n,
length ℓ_n
13
12
21
DISPERSION-MANAGED
(DM) CAVITY
11
PERIODIC
DRIVE
15
OPTICAL
BANDPASS
FILTER
OUTPUT
COUPLER
ANOMALOUS-
DISPERSION FIBER
Dispersion β_a,
length ℓ_a
24
19

Figure 1b

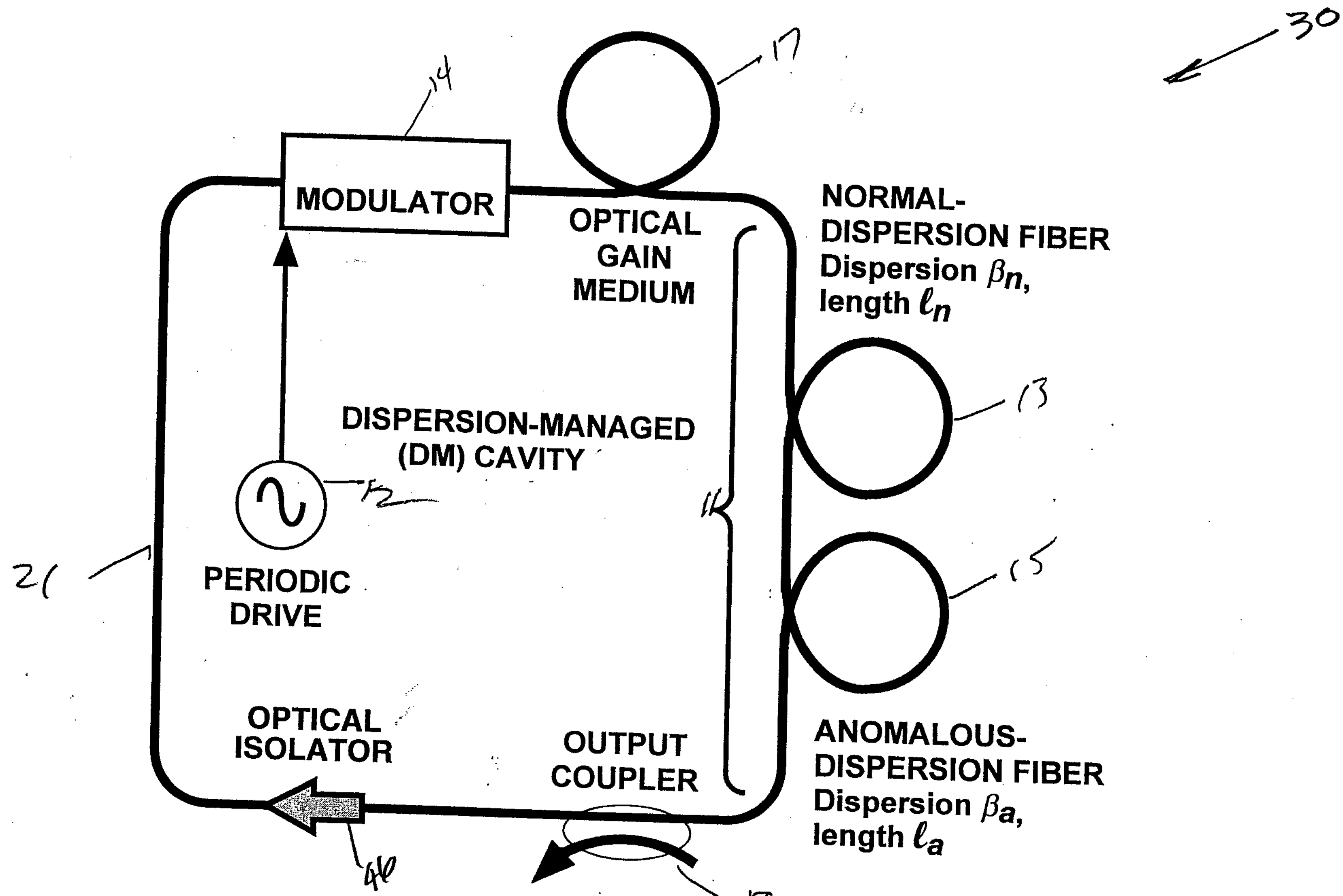
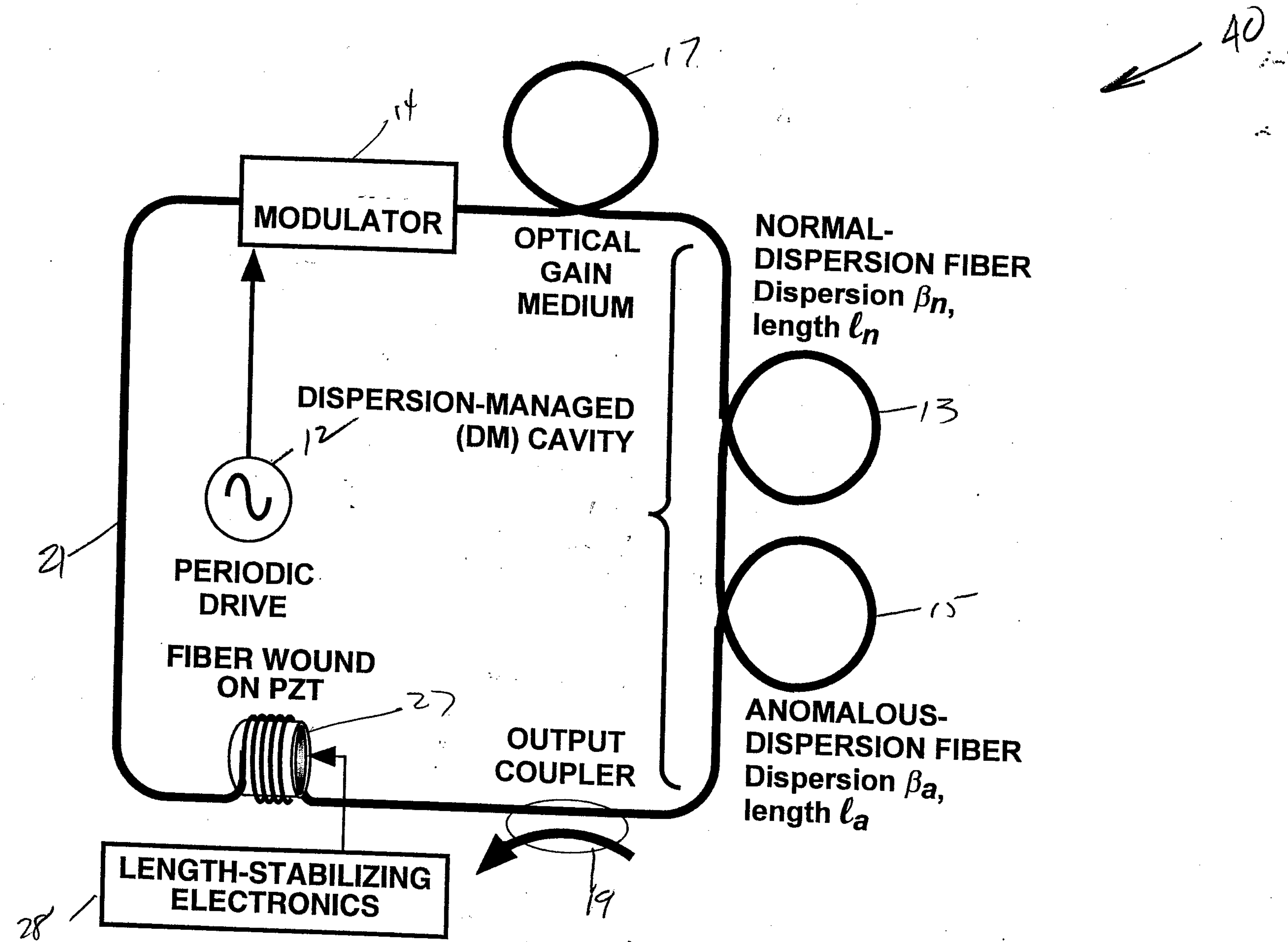

30
MODULATOR
14
17
OPTICAL
GAIN
MEDIUM
NORMAL-
DISPERSION FIBER
Dispersion β_n,
length ℓ_n
13
DISPERSION-MANAGED
(DM) CAVITY
12
11
15
21
PERIODIC
DRIVE
ANOMALOUS-
DISPERSION FIBER
Dispersion β_a,
length ℓ_a
OPTICAL
ISOLATOR
OUTPUT
COUPLER
46
19

Figure 1c


40
MODULATOR
14
17
OPTICAL
GAIN
MEDIUM
NORMAL-
DISPERSION FIBER
Dispersion β_n,
length ℓ_n
13
DISPERSION-MANAGED
(DM) CAVITY
12
21
PERIODIC
DRIVE
15
FIBER WOUND
ON PZT
27
OUTPUT
COUPLER
ANOMALOUS-
DISPERSION FIBER
Dispersion β_a,
length ℓ_a
LENGTH-STABILIZING
ELECTRONICS
28
19
Figure 1d

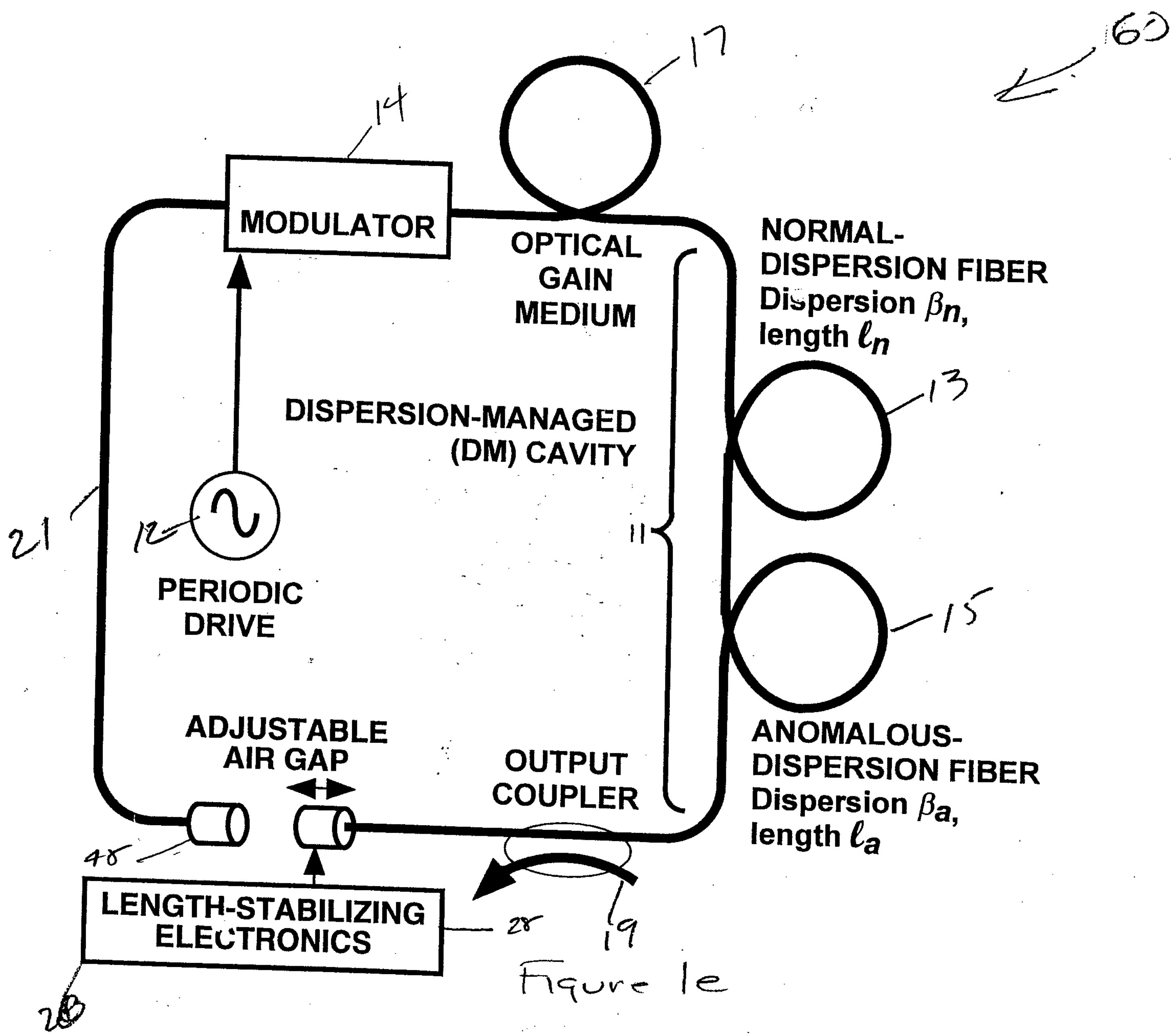

60
14
MODULATOR
17
OPTICAL
GAIN
MEDIUM
NORMAL-
DISPERSION FIBER
Dispersion β_n,
length ℓ_n
13
DISPERSION-MANAGED
(DM) CAVITY
21
12
PERIODIC
DRIVE
15
ADJUSTABLE
AIR GAP
OUTPUT
COUPLER
ANOMALOUS-
DISPERSION FIBER
Dispersion β_a,
length ℓ_a
48
LENGTH-STABILIZING
ELECTRONICS
28
19
28

Figure 1e

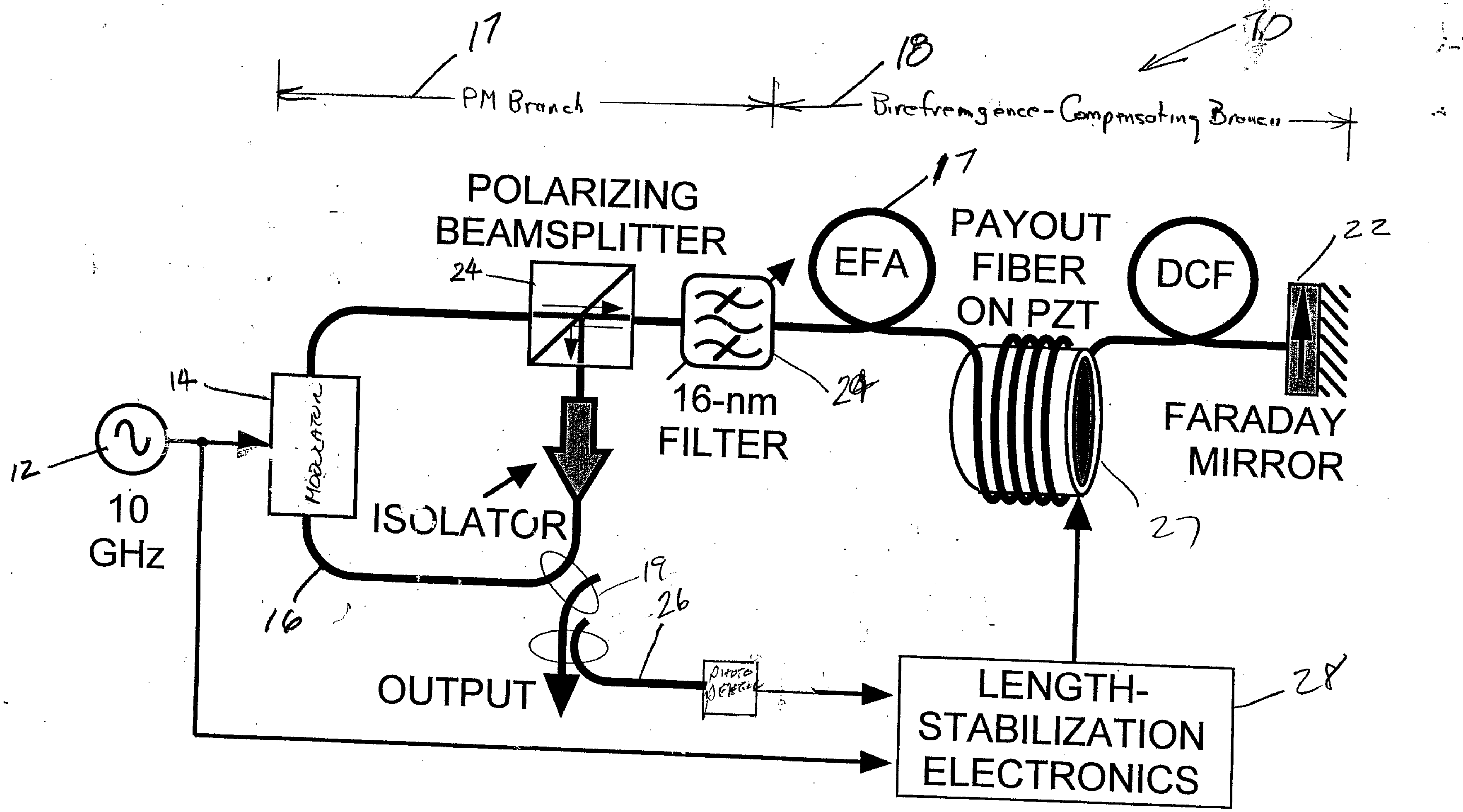
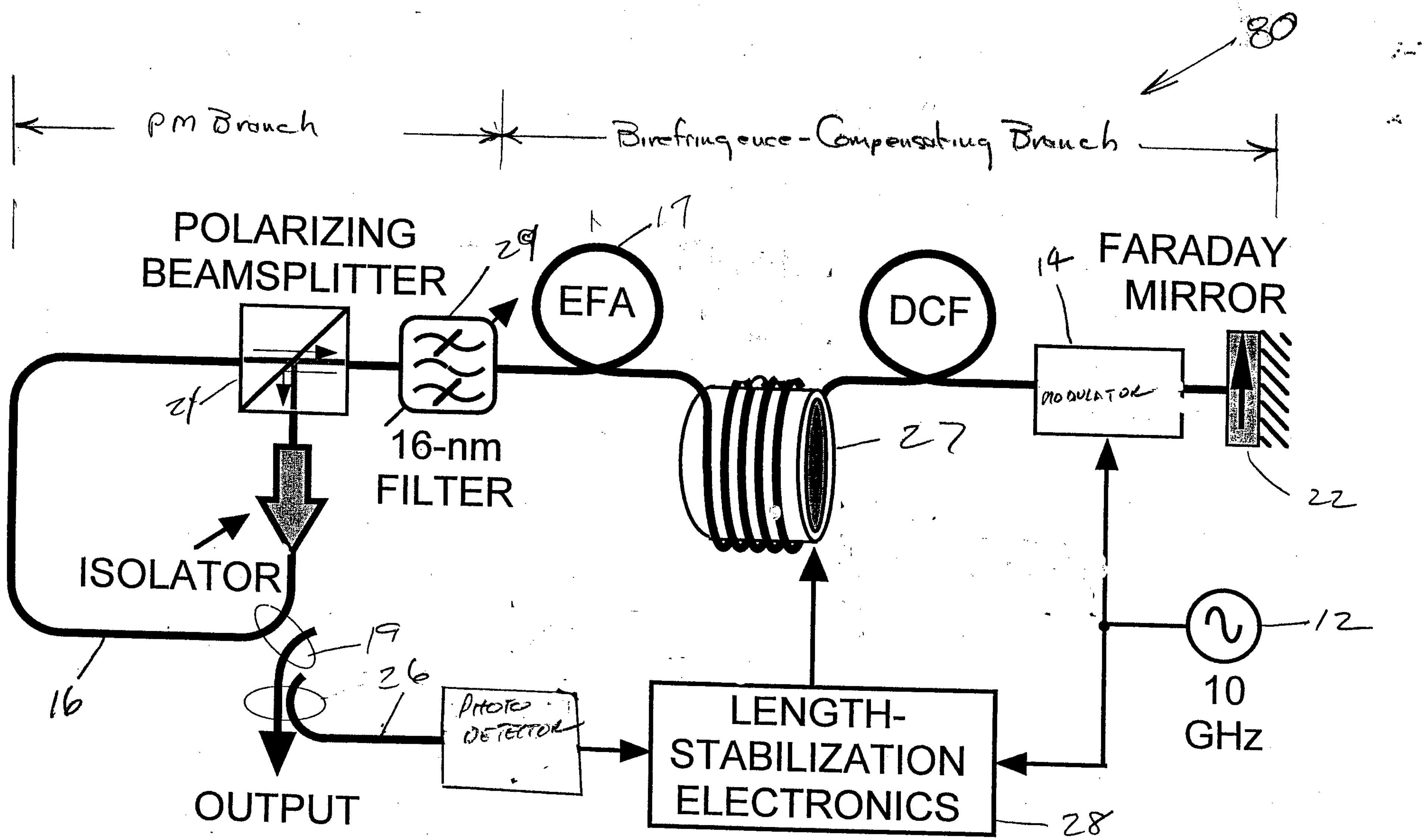

PM Branch
Birefringence-Compensating Branch
POLARIZING
BEAMSPLITTER
16-nm
FILTER
EFA
PAYOUT
FIBER
ON PZT
DCF
FARADAY
MIRROR
10
GHz
MODULATOR
ISOLATOR
OUTPUT
PHOTO DETECTOR
LENGTH-
STABILIZATION
ELECTRONICS
10
12
14
16
17
18
19
20
22
24
26
27
28

Figure 2a



80
PM Branch
Birefringence-Compensating Branch
POLARIZING
BEAMSPLITTER
16-nm
FILTER
EFA
DCF
FARADAY
MIRROR
MODULATOR
ISOLATOR
OUTPUT
PHOTO DETECTOR
LENGTH-
STABILIZATION
ELECTRONICS
10
GHz
12
14
16
17
19
21
22
26
27
28
29

Figure 26

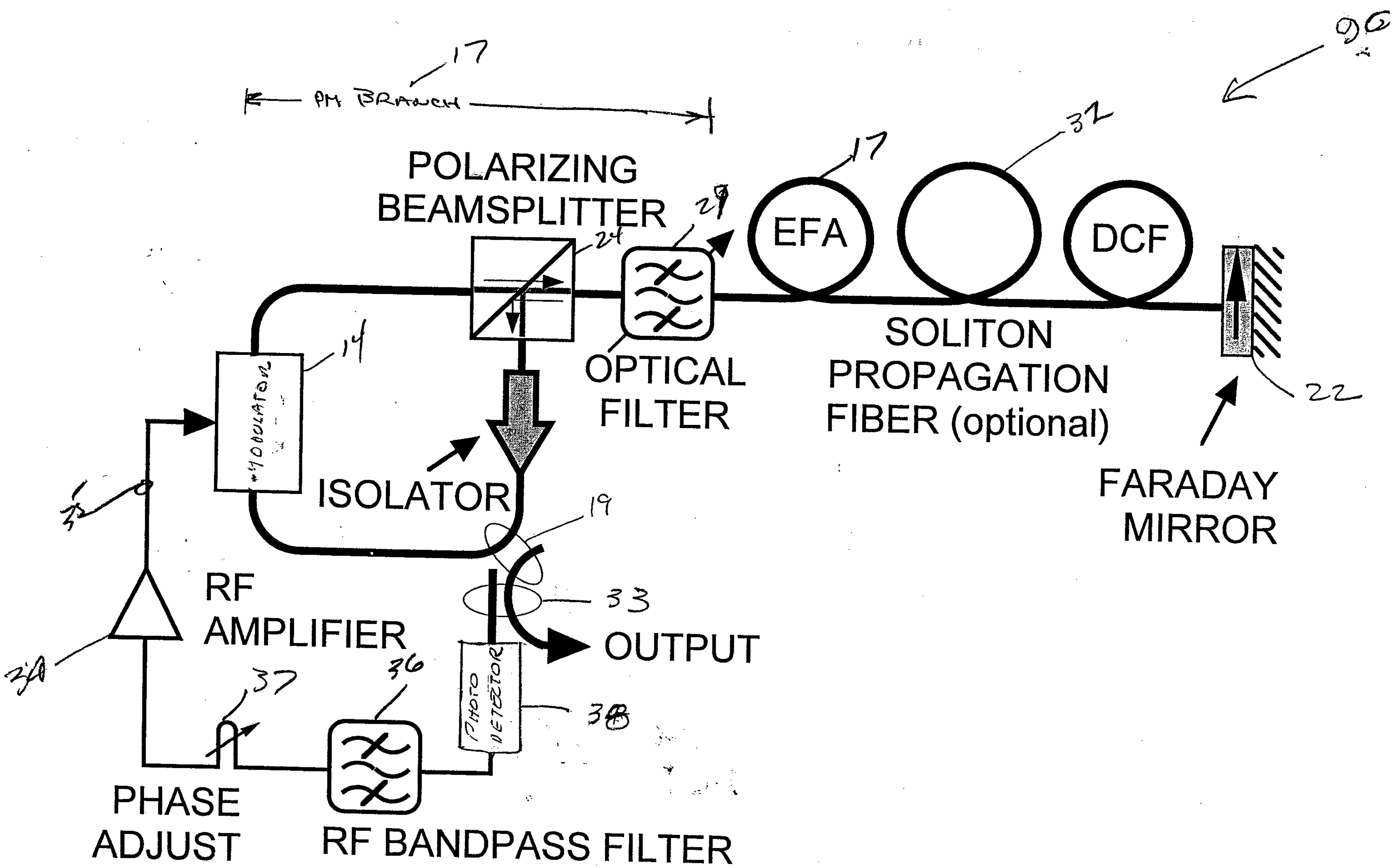
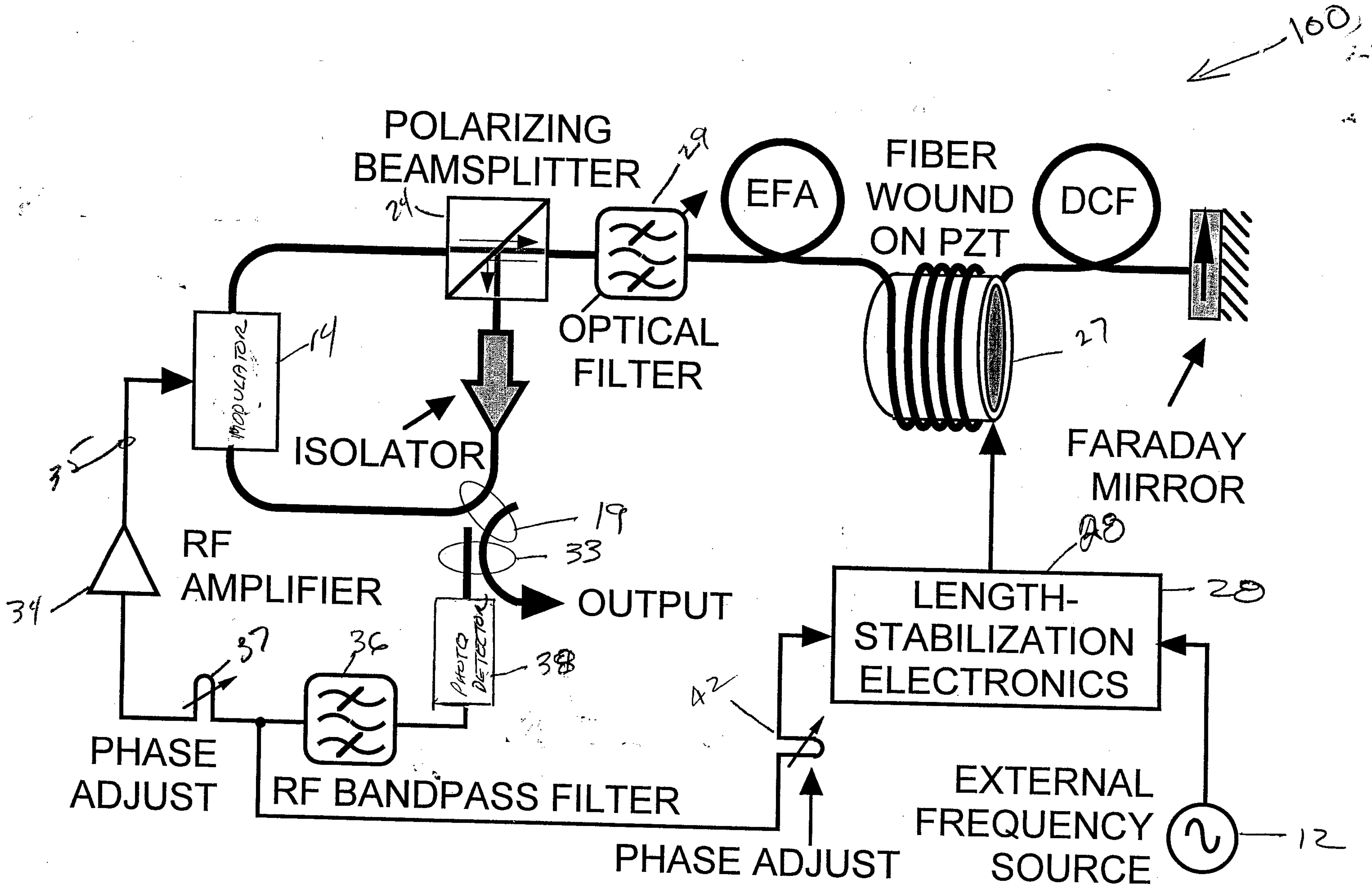

90
PM BRANCH
17
POLARIZING
BEAMSPLITTER
24
29
EFA
17
32
DCF
MODULATOR
14
OPTICAL
FILTER
SOLITON
PROPAGATION
FIBER (optional)
22
FARADAY
MIRROR
ISOLATOR
19
33
OUTPUT
RF
AMPLIFIER
34
35
37
36
PHOTO DETECTOR
38
PHASE
ADJUST
RF BANDPASS FILTER

Figure 2c



Regeneratively mode-locked laser with length stabilization.

Figure 2d

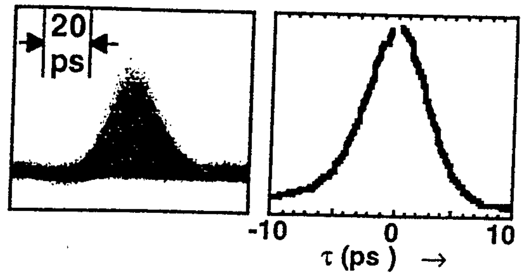


Fig. 3a

I. $P_{out}/P_{max} = 0.047$

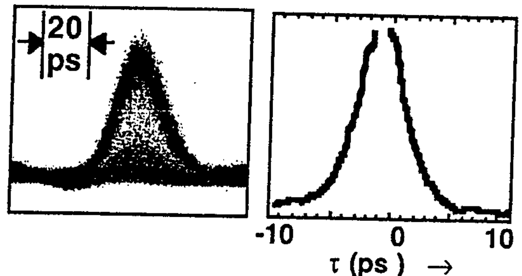


Fig. 3b

IIa. $P_{out}/P_{max} = 0.064$

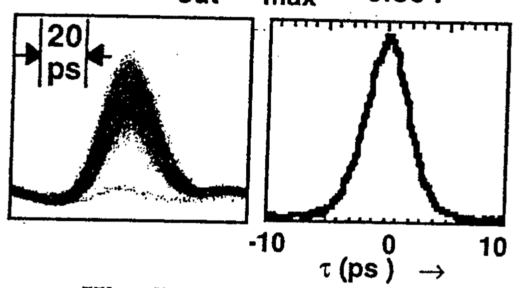


Fig 3c

IIb. $P_{out}/P_{max} = 0.27$

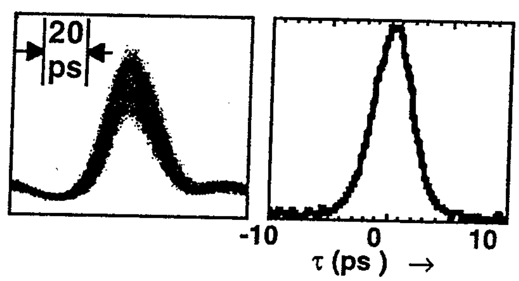


Fig 3d

IIIa. $P_{out}/P_{max} = 0.34$

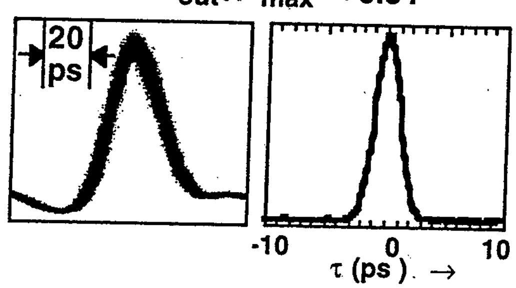
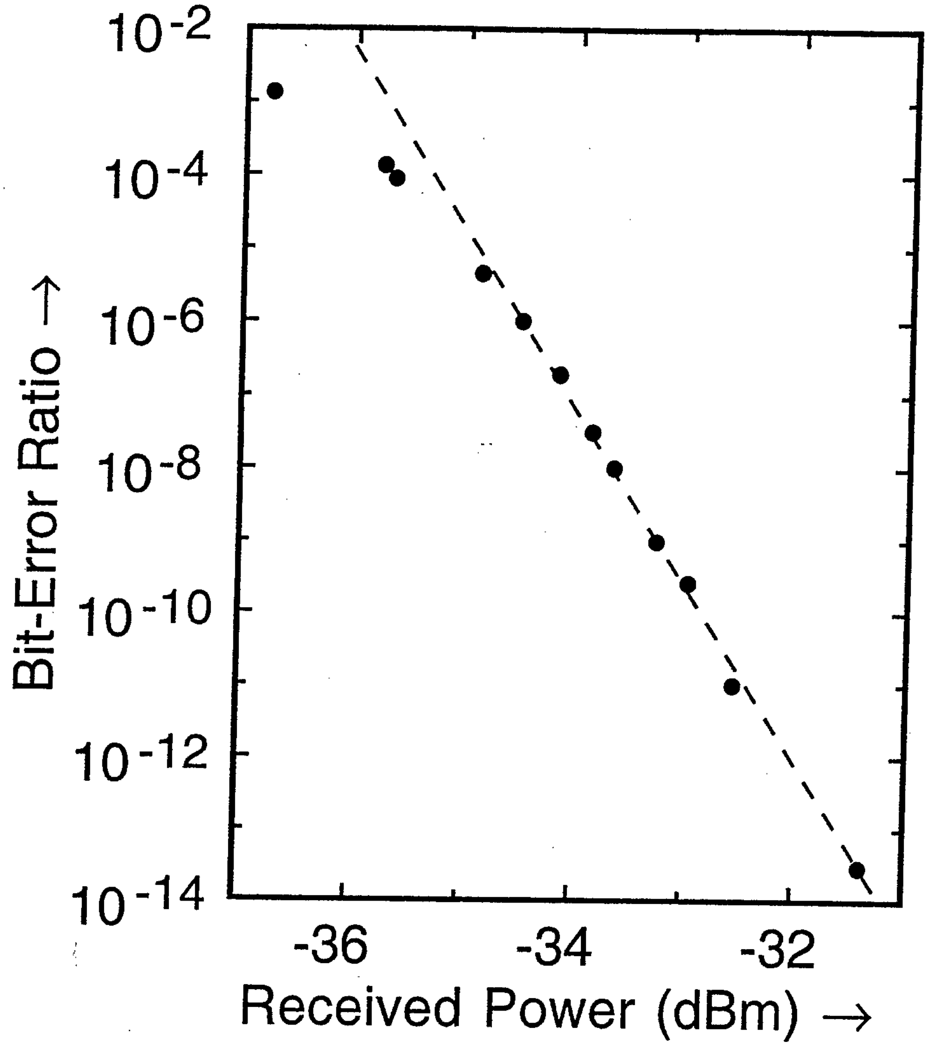


Fig 3e

IIIb. $P_{out}/P_{max} = 1.00$



10-2
10-4
10-6
10-8
10-10
10-12
10-14
Bit-Error Ratio →
-36
-34
-32
Received Power (dBm) →

FIGURE 4

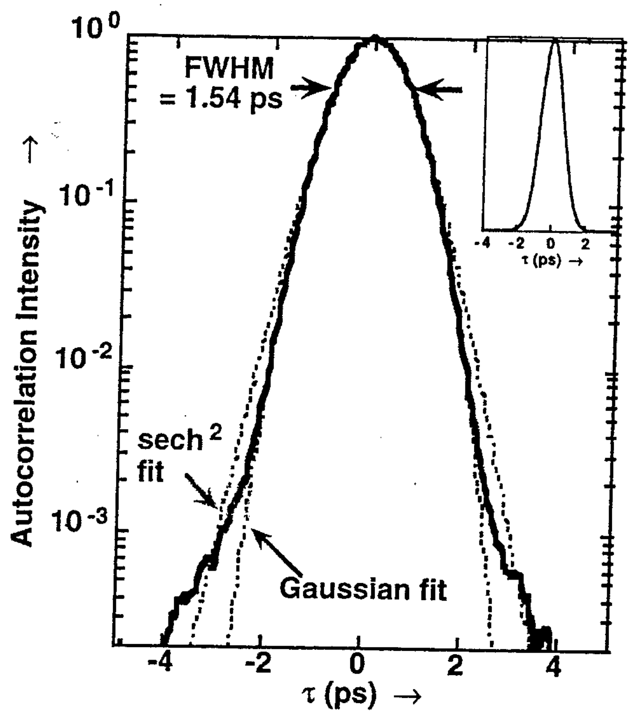


Figure 5a

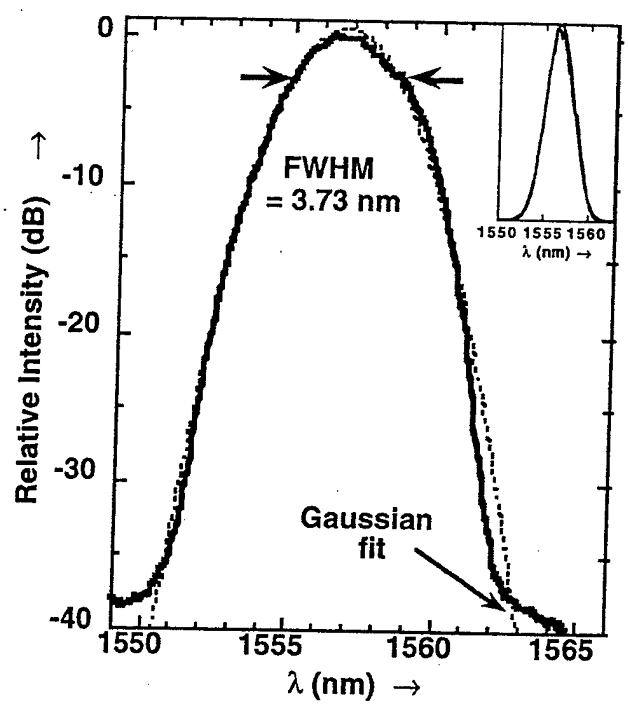


Figure 5b

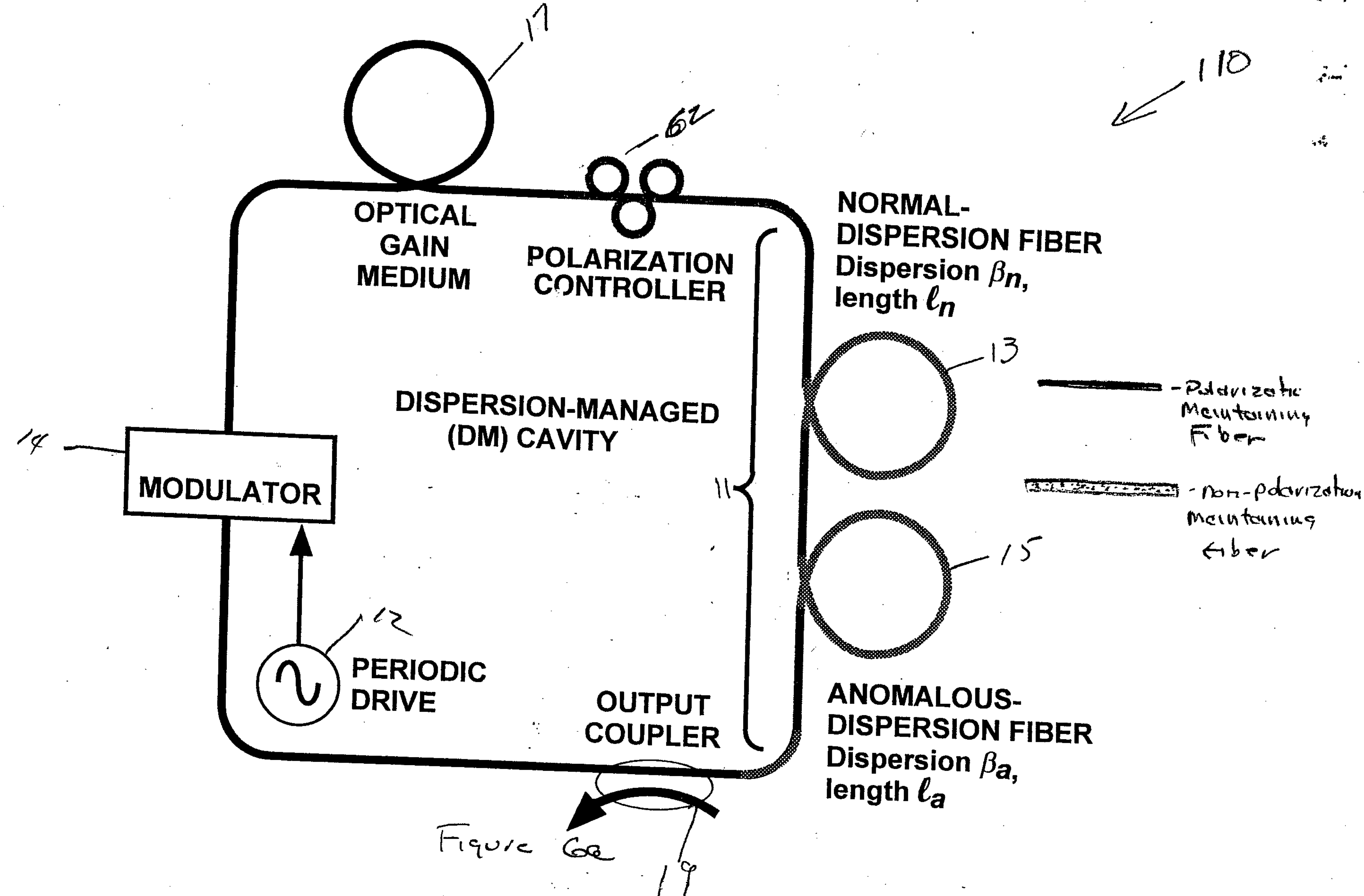

110
17
62
OPTICAL GAIN MEDIUM
POLARIZATION CONTROLLER
NORMAL-DISPERSION FIBER Dispersion β_n, length ℓ_n
13
- Polarization Maintaining Fiber
- Non-polarization Maintaining Fiber
15
14
MODULATOR
DISPERSION-MANAGED (DM) CAVITY
11
12
PERIODIC DRIVE
OUTPUT COUPLER
ANOMALOUS-DISPERSION FIBER Dispersion β_a, length ℓ_a
19

Figure 6a

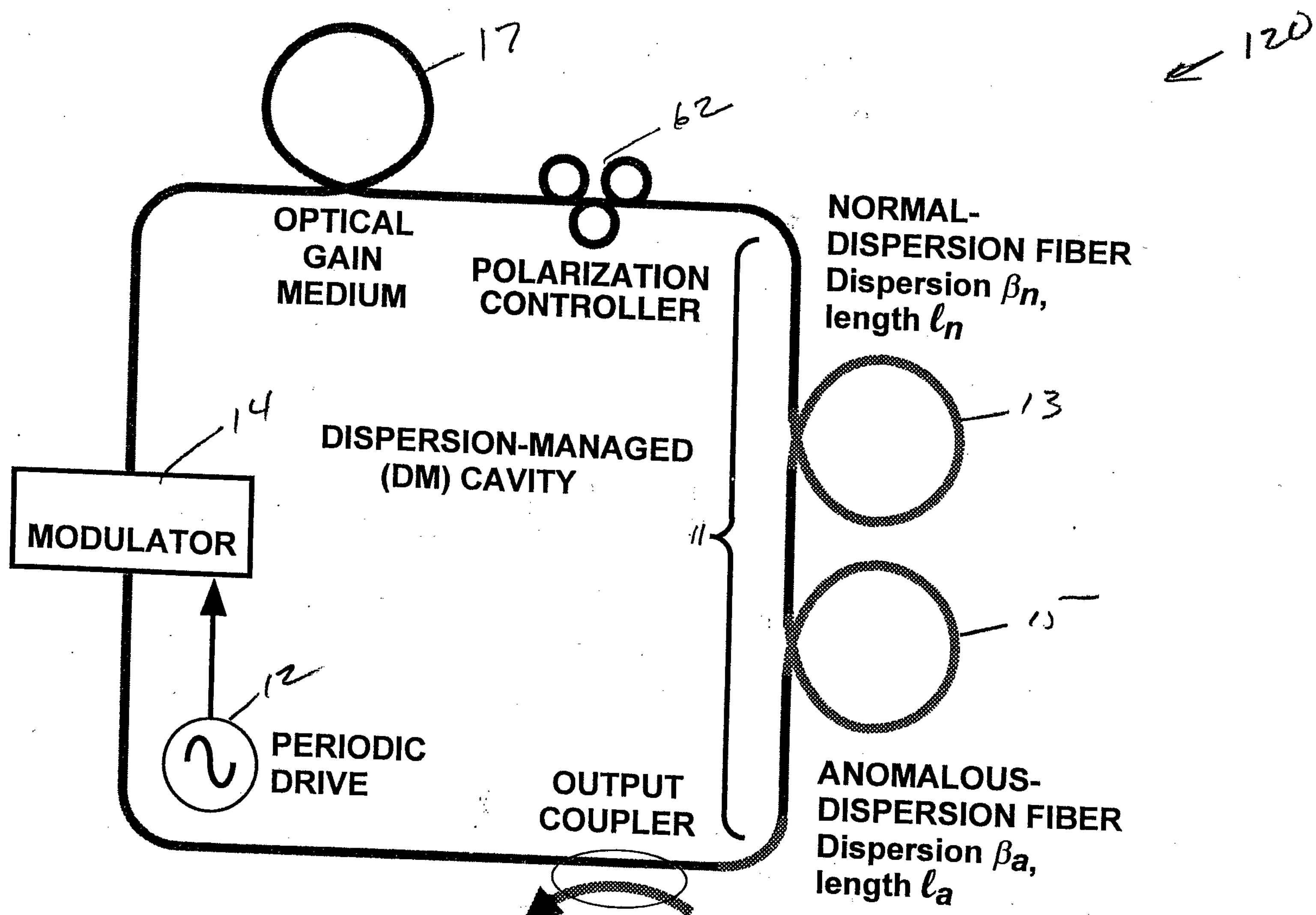
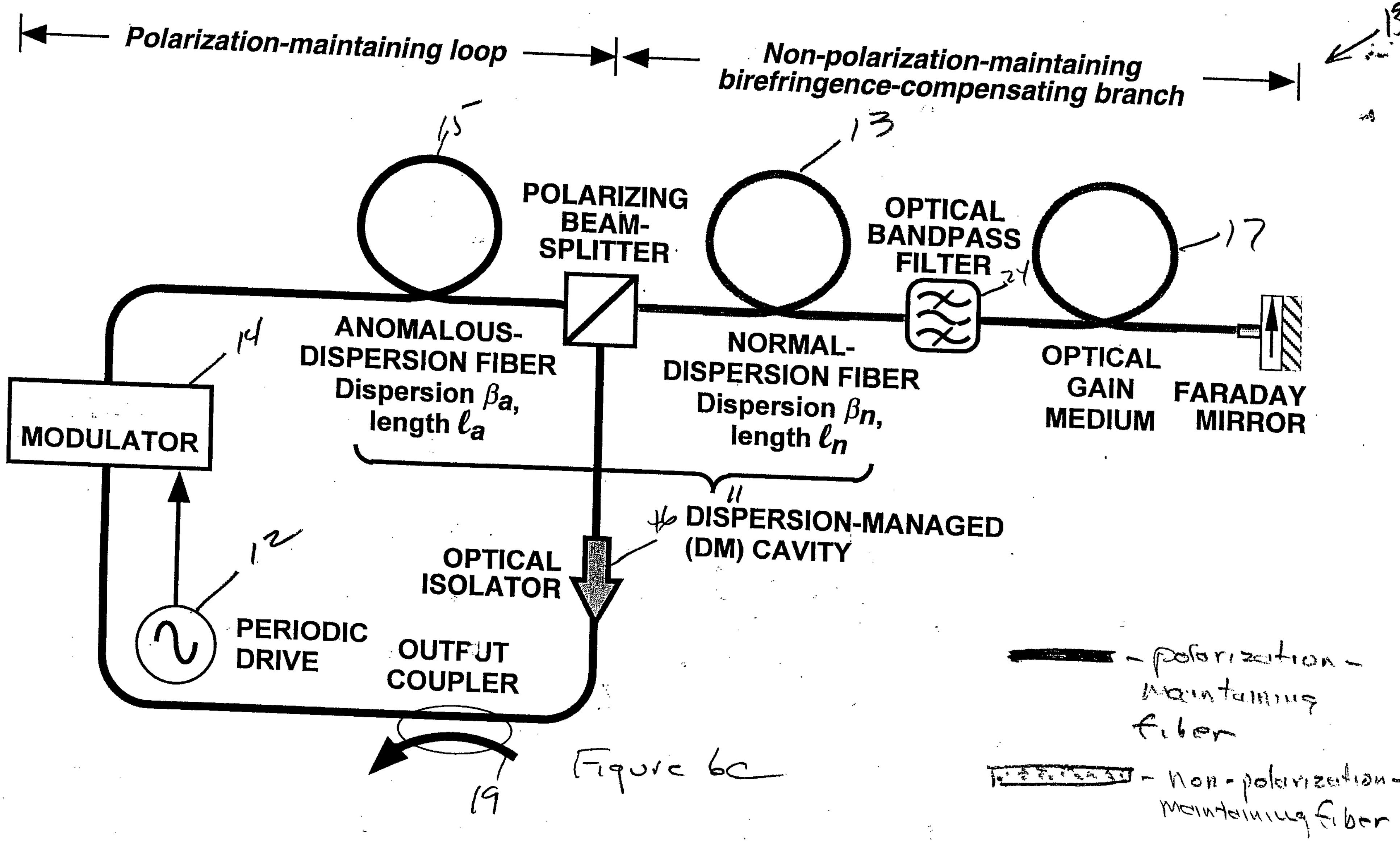

120
17
62
OPTICAL
GAIN
MEDIUM
POLARIZATION
CONTROLLER
NORMAL-
DISPERSION FIBER
Dispersion β_n,
length ℓ_n
14
13
DISPERSION-MANAGED
(DM) CAVITY
MODULATOR
11
15
12
PERIODIC
DRIVE
OUTPUT
COUPLER
ANOMALOUS-
DISPERSION FIBER
Dispersion β_a,
length ℓ_a
19

Figure 6b



Polarization-maintaining loop
Non-polarization-maintaining birefringence-compensating branch
POLARIZING BEAM-SPLITTER
OPTICAL BANDPASS FILTER
ANOMALOUS-DISPERSION FIBER
Dispersion β_a, length ℓ_a
NORMAL-DISPERSION FIBER
Dispersion β_n, length ℓ_n
OPTICAL GAIN MEDIUM
FARADAY MIRROR
MODULATOR
DISPERSION-MANAGED (DM) CAVITY
OPTICAL ISOLATOR
PERIODIC DRIVE
OUTPUT COUPLER
- polarization-maintaining fiber
- non-polarization-maintaining fiber

Figure 6c

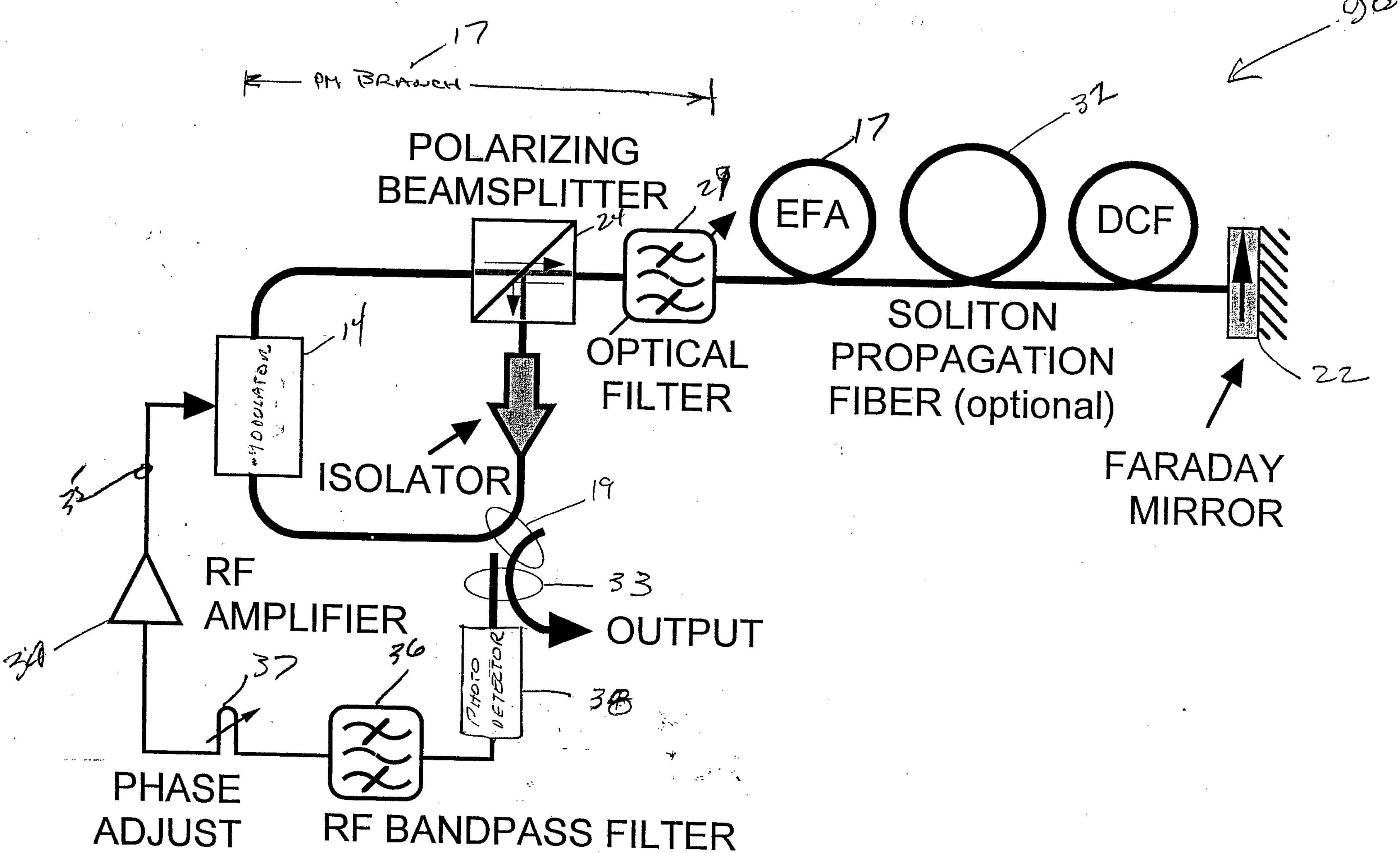
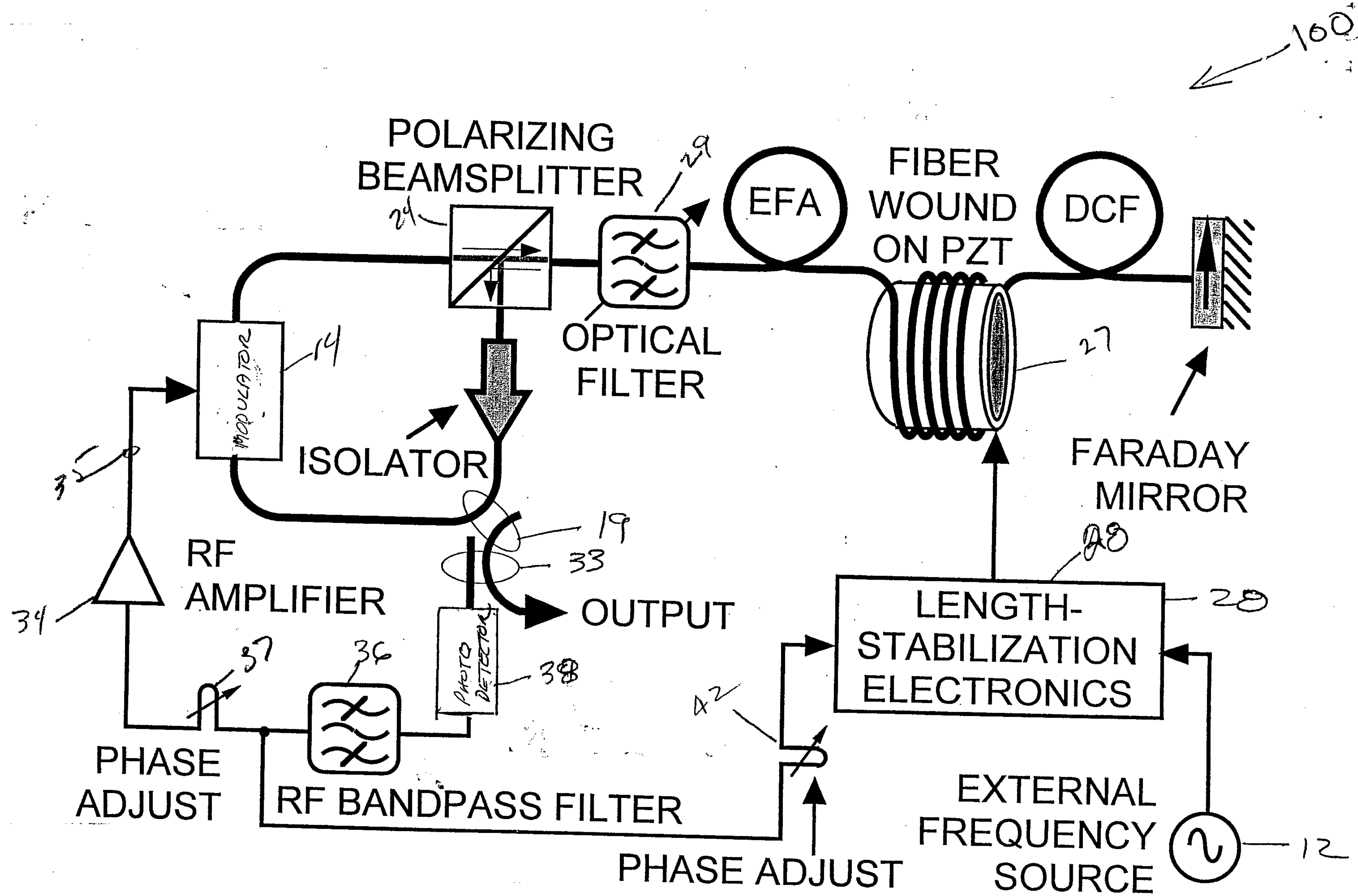

PM BRANCH
POLARIZING BEAMSPLITTER
EFA
DCF
OPTICAL FILTER
SOLITON PROPAGATION FIBER (optional)
FARADAY MIRROR
MODULATOR
ISOLATOR
RF AMPLIFIER
OUTPUT
PHOTO DETECTOR
PHASE ADJUST
RF BANDPASS FILTER

Figure 2C



Regeneratively mode-locked laser with length stabilization.

Figure 2d

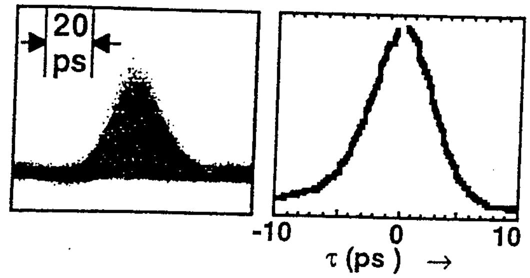


Fig. 3a

I. $P_{out}/P_{max} = 0.047$

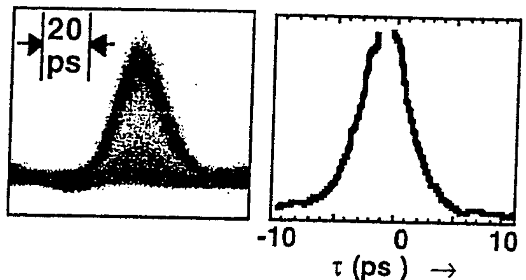


Fig. 3b

IIa. $P_{out}/P_{max} = 0.064$

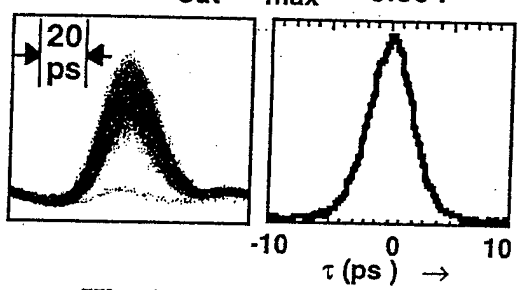


Fig 3c

IIb. $P_{out}/P_{max} = 0.27$

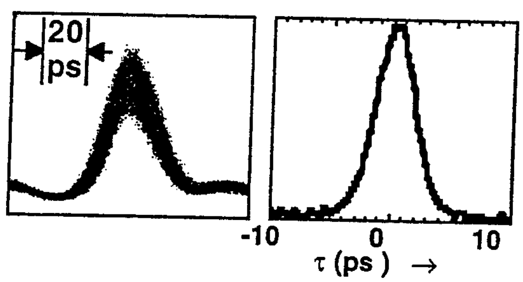


Fig 3d

IIIa. $P_{out}/P_{max} = 0.34$

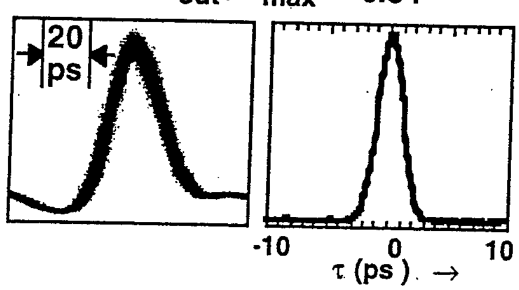


Fig 3e

IIIb. $P_{out}/P_{max} = 1.00$

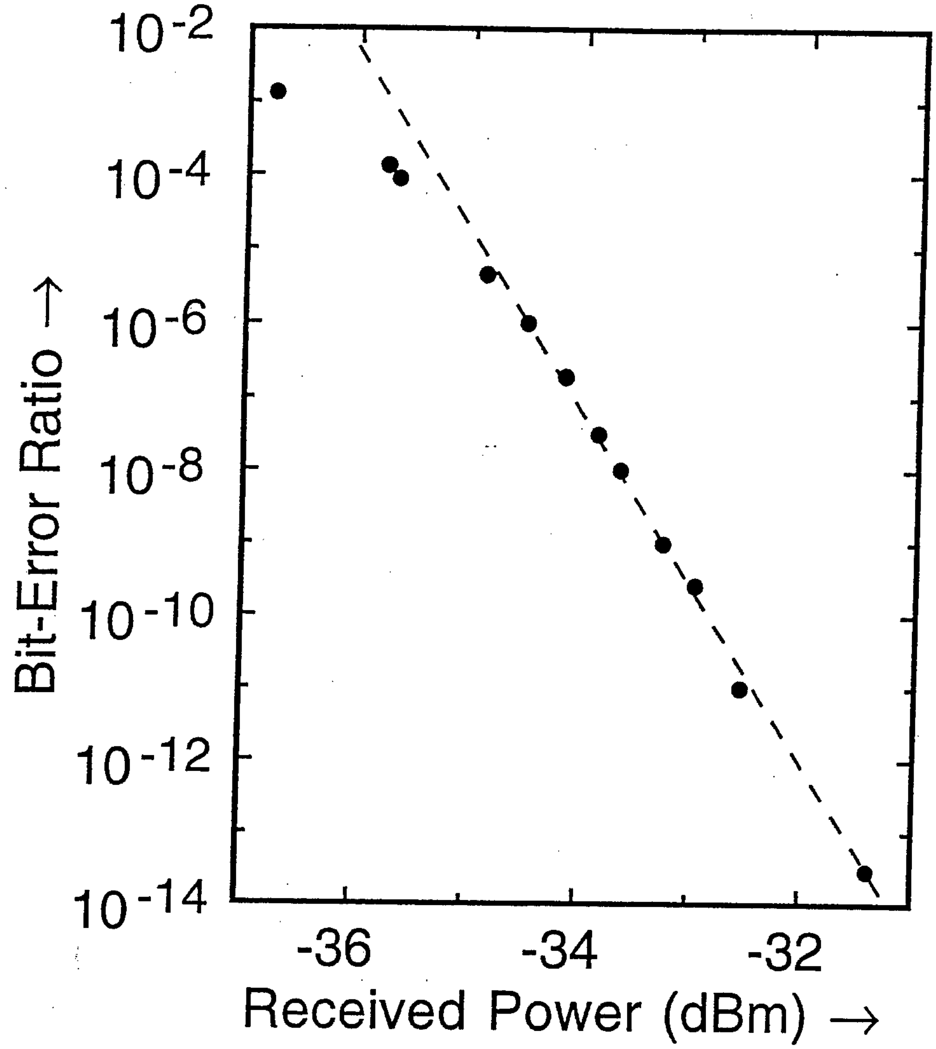

Bit-Error Ratio →
10-2
10-4
10-6
10-8
10-10
10-12
10-14
-36
-34
-32
Received Power (dBm) →

FIGURE 4

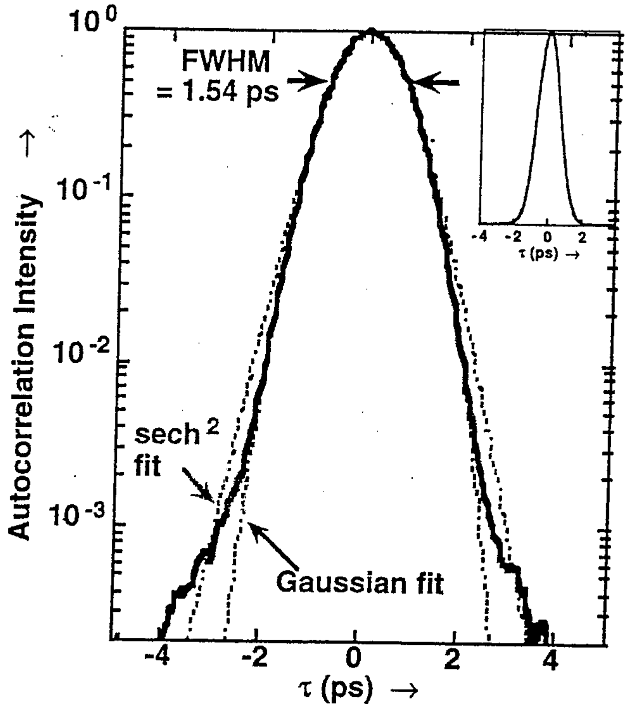


Figure 5a

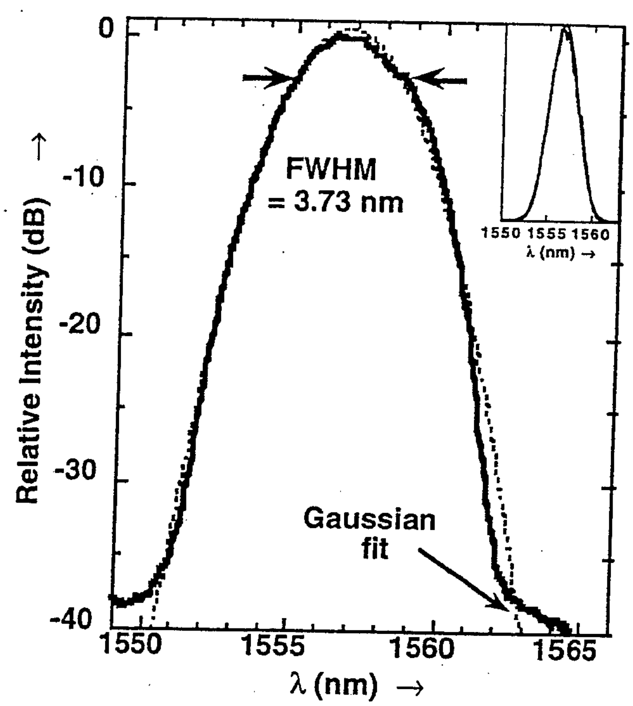


Figure 5b

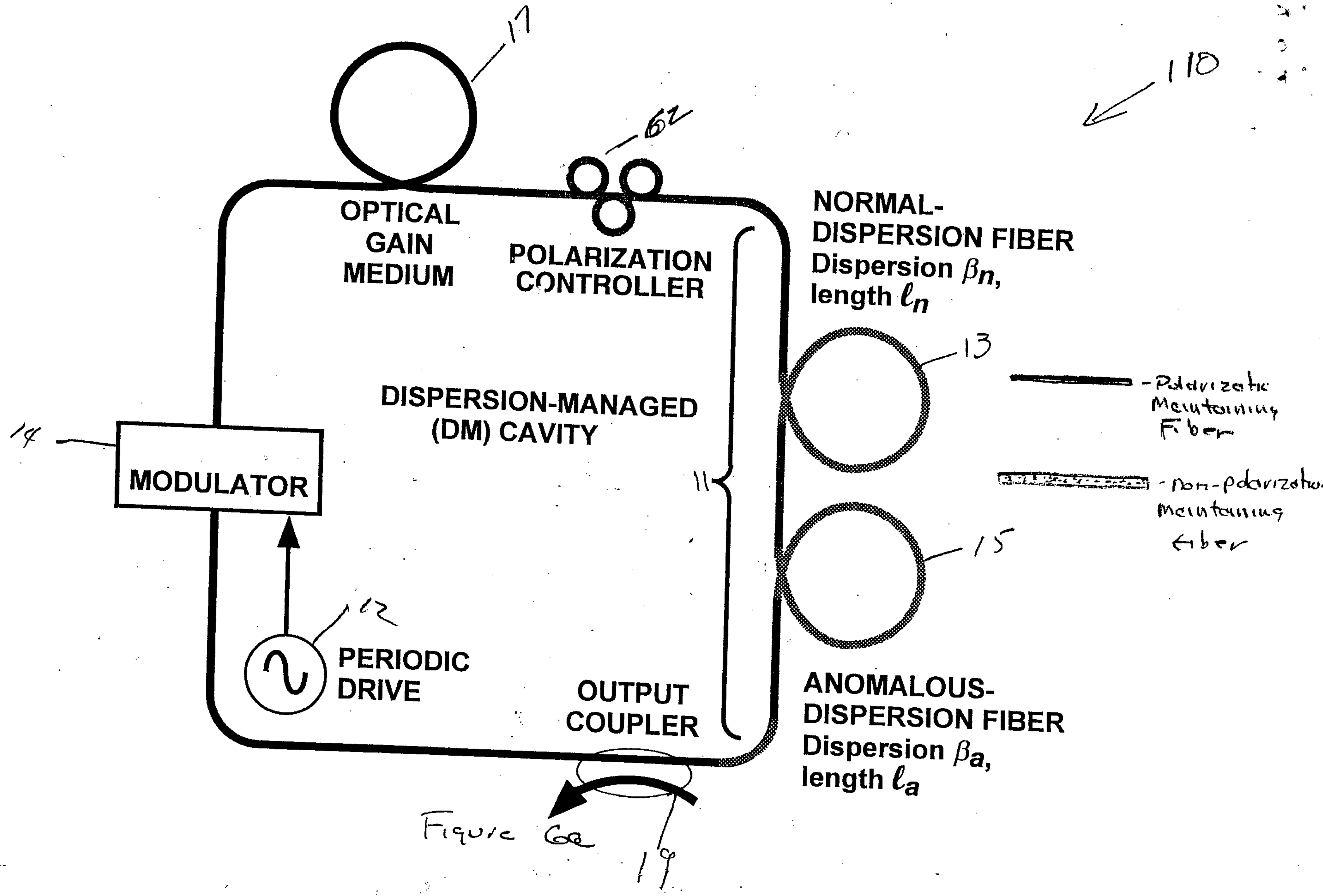
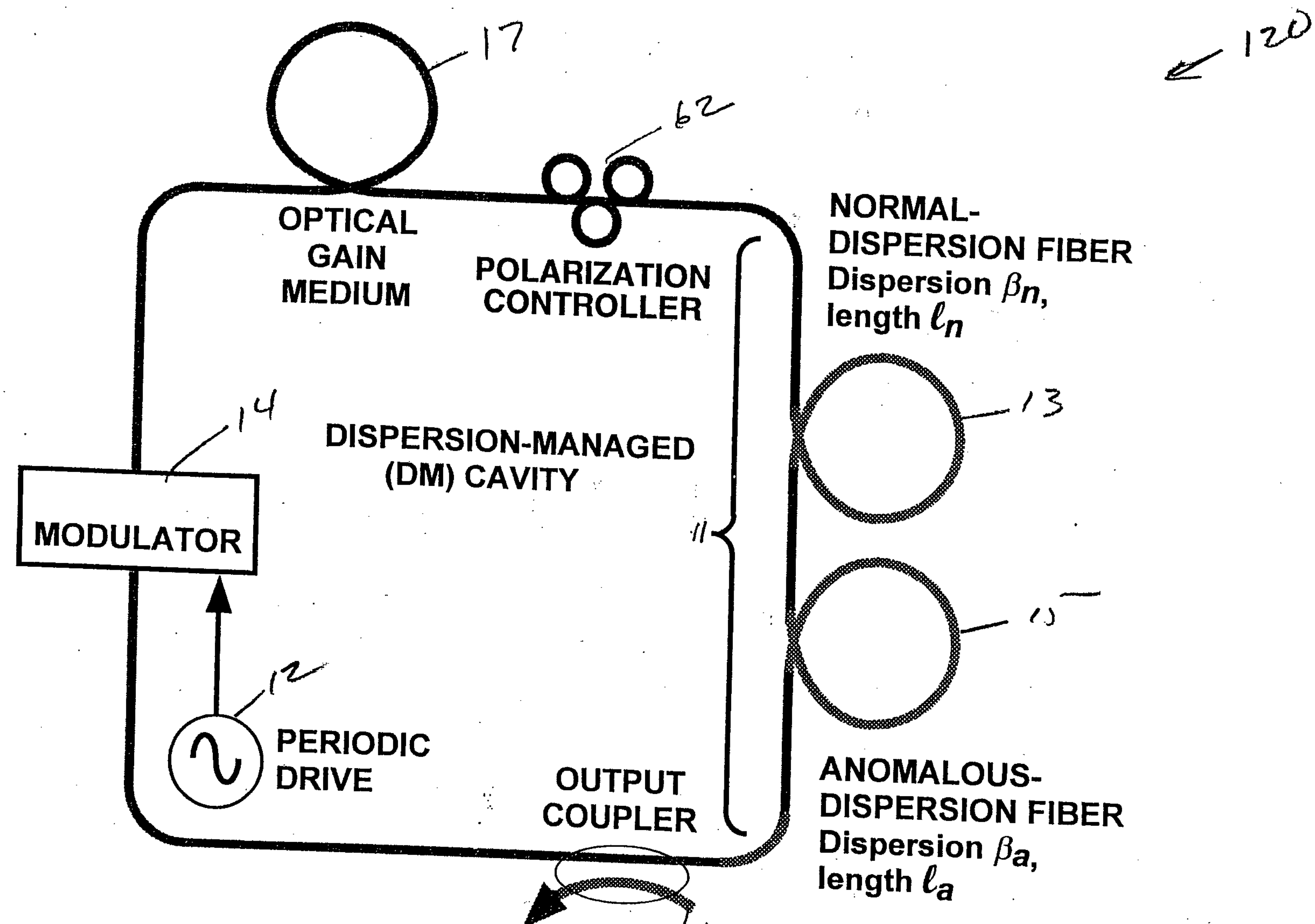
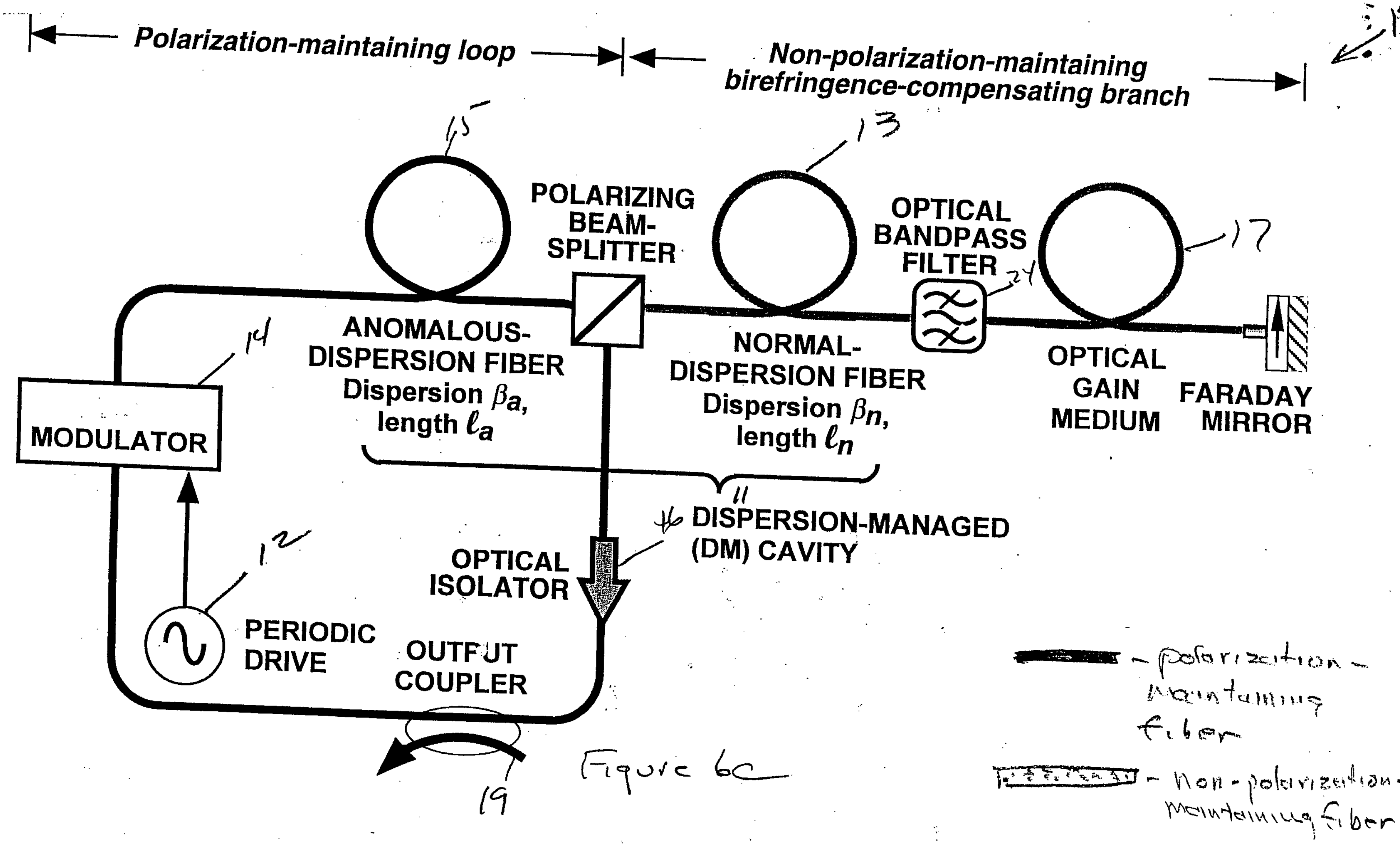

110
17
OPTICAL GAIN MEDIUM
62
POLARIZATION CONTROLLER
NORMAL-DISPERSION FIBER Dispersion β_n, length ℓ_n
13
- Polarization Maintaining Fiber
- Non-polarization Maintaining Fiber
15
ANOMALOUS-DISPERSION FIBER Dispersion β_a, length ℓ_a
11
DISPERSION-MANAGED (DM) CAVITY
14
MODULATOR
12
PERIODIC DRIVE
OUTPUT COUPLER
19

Figure 6a



120
17
62
OPTICAL GAIN MEDIUM
POLARIZATION CONTROLLER
NORMAL-DISPERSION FIBER Dispersion β_n, length ℓ_n
13
14
MODULATOR
DISPERSION-MANAGED (DM) CAVITY
11
15
12
PERIODIC DRIVE
OUTPUT COUPLER
ANOMALOUS-DISPERSION FIBER Dispersion β_a, length ℓ_a
19

Figure 6b



Polarization-maintaining loop
Non-polarization-maintaining birefringence-compensating branch
POLARIZING BEAM-SPLITTER
OPTICAL BANDPASS FILTER
MODULATOR
ANOMALOUS-DISPERSION FIBER Dispersion βa, length ℓa
NORMAL-DISPERSION FIBER Dispersion βn, length ℓn
OPTICAL GAIN MEDIUM
FARADAY MIRROR
DISPERSION-MANAGED (DM) CAVITY
OPTICAL ISOLATOR
PERIODIC DRIVE
OUTPUT COUPLER
- polarization-maintaining fiber
- non-polarization-maintaining fiber

Figure 6c