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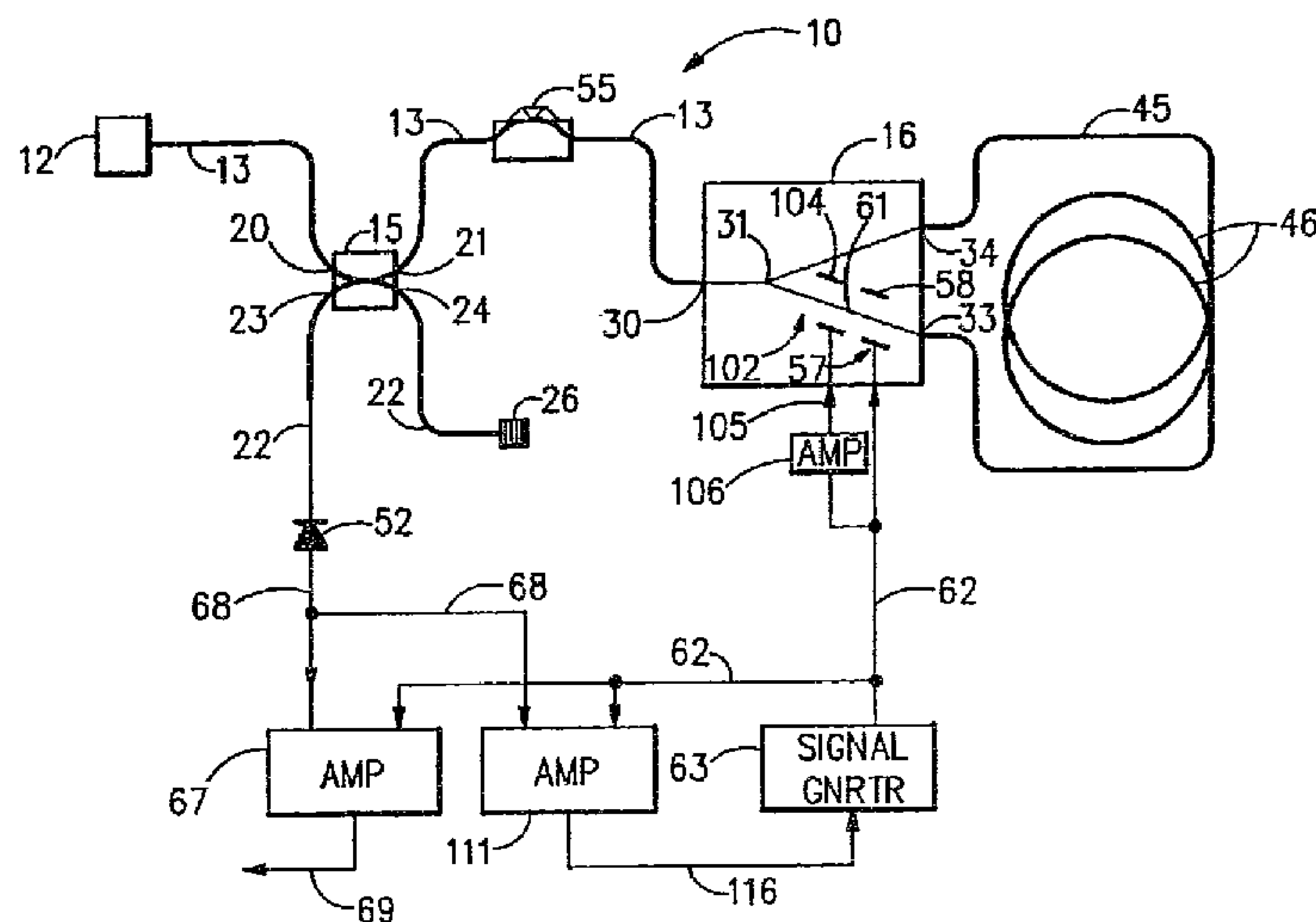
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(54) **COMMANDE DE FREQUENCE DE MODULATION POUR
DETECTEUR DE ROTATION A FIBRE OPTIQUE**

(54) **MODULATION FREQUENCY CONTROL IN A FIBER OPTIC
ROTATION SENSOR**



(57) Dans un détecteur de rotation à fibre optique possédant une paire de faisceaux lumineux en contre-propagation dans une boucle de guides d'ondes optiques, un modulateur de phase est commandé par un signal de modulation à la fréquence propre de la boucle. Lorsqu'elles quittent la boucle, les ondes se rassemblent pour former un signal d'intensité lumineuse qui est détecté. Le signal détecté comporte un élément en quadrature avec un élément de vitesse de rotation voulue, et l'ampleur de l'élément en quadrature est proportionnelle aux déviations quelconques de la fréquence du signal de modulation de la fréquence propre de la boucle. Le modulateur de phase est servocommandé de sorte que l'élément en quadrature soit remis à zéro, ce qui compense les déviations quelconques de la fréquence du modulateur de la fréquence propre de la boucle.

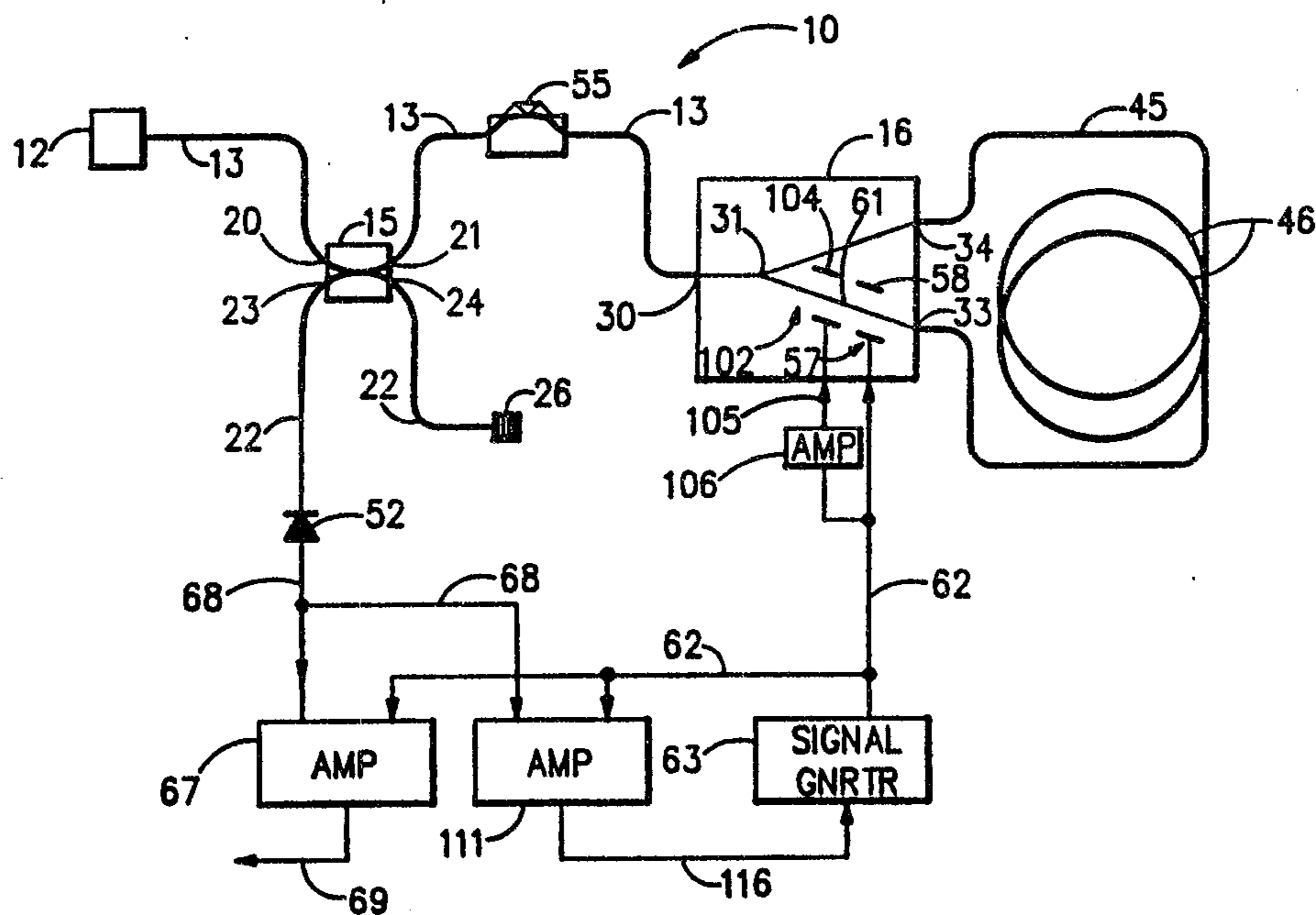
(57) In a fiber optic rotation sensor having a pair of light waves counter-propagating in an optical waveguide loop, a phase modulator is driven by a modulating signal at the loop eigenfrequency. Upon exiting the loop the waves are combined into a light intensity signal which is sensed, the sensed signal including a component in quadrature with a desired rotation rate component, the magnitude of the quadrature component being proportional to any deviations in the frequency of the modulating signal from the loop eigenfrequency. The phase modulator is servo-controlled so as to drive the quadrature component to zero, thereby compensating for any deviations in the modulator frequency from the loop eigenfrequency.



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<p>(21) International Application Number: PCT/US91/03701 (22) International Filing Date: 24 May 1991 (24.05.91) (30) Priority data: 533,196 4 June 1990 (04.06.90) US (71) Applicant: UNITED TECHNOLOGIES CORPORATION [US/US]; United Technologies Building, Hartford, CT 06101 (US). (72) Inventor: FERRAR, Carl, M. ; 114 Wildflower Rd., East Hartford, CT 06118 (US). (74) Agents: KOSAKOWSKI, Richard, H. et al.; Patent Department, United Technologies Corporation, Hartford, CT 06101 (US).</p>		<p>(81) Designated States: AT (European patent), BE (European patent), CA, CH (European patent), DE (European patent), DK (European patent), ES (European patent), FR (European patent), GB (European patent), GR (European patent), IT (European patent), JP, LU (European patent), NL (European patent), SE (European patent).</p> <p>Published <i>With international search report. Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</i></p>

(54) Title: MODULATION FREQUENCY CONTROL IN A FIBER OPTIC ROTATION SENSOR



(57) Abstract

In a fiber optic rotation sensor having a pair of light waves counter-propagating in an optical waveguide loop, a phase modulator is driven by a modulating signal at the loop eigenfrequency. Upon exiting the loop the waves are combined into a light intensity signal which is sensed, the sensed signal including a component in quadrature with a desired rotation rate component, the magnitude of the quadrature component being proportional to any deviations in the frequency of the modulating signal from the loop eigenfrequency. The phase modulator is servo-controlled so as to drive the quadrature component to zero, thereby compensating for any deviations in the modulator frequency from the loop eigenfrequency.

MODULATION FREQUENCY CONTROL IN A
FIBER OPTIC ROTATION SENSOR

Technical Field

This invention relates to fiber optic rotation
5 sensors, and more particularly to modulator frequency
control in a fiber optic gyroscope.

Background of the Invention

Interferometric signal analysis involves the
determination of signal wavelength, wave velocities,
10 distances and directions using interference phenomena
between two signals. Particular application may include
optical signal analysis in a fiber optic gyroscope
(FOG).

A FOG includes a light source, e.g., a laser diode,
15 which provides coherent or semi-coherent light split
into two substantially equal waves which
counter-propagate in a coil of fiber optic waveguide.
The waves are recombined interferometrically at the coil
output such that the light intensity seen by a detector
20 depends on the relative phases thereof.

When the coil rotates about a normal axis, the
waves take different times to traverse the coil. This
non-reciprocal phenomenon, known as the Sagnac effect,
causes a change (shift) in the relative phase between
25 the waves at a detector and, therefore, a change in the
light intensity signal at the detector. Depending on
the initial phase difference, which can be controlled
by, e.g., application of suitable phase modulation at
one end of the coil, the magnitude and direction, e.g.,
30 increase or decrease, of the change in the light
intensity signal are dependent upon, respectively, the

rate and sense of the rotation applied to the coil about the axis.

German document DE-A-3 436 249 appears to disclose a fiber optic gyro having a light source, a splitter, an optical waveguide loop having counterpropagating light waves, a signal generator, a phase modulator in the loop, light wave combiner, a detector and a feedback loop connected between the detector and phase modulator.

European Patent Office document EP-A-0 245 118 discloses a fiber optic gyro having a feedback loop that adjusts a phase modulator in a loop in accordance with an edge sensitive detector in the feedback loop.

The detector signal intensity is a cosine function, and, thus, is relatively insensitive to small rotation rates. It is known to induce an optical phase modulation (phase dither) at a relatively high frequency, e.g., a sinusoid or square wave, on the counter-propagating waves to both increase FOG sensitivity and to determine the change in direction of FOG rotation. Additionally, control of the modulation frequency at the relatively high frequency (typically at the loop eigenfrequency) shifts the measurement bandwidth away from lower frequencies subject to excess noise. A phase modulator at one end of the coil is driven at a frequency corresponding to the coil eigenfrequency. The detector signal intensity is a function of both the modulation and rotation induced phase differences between the counter-propagating waves.

However, the eigenfrequency is dependent upon physical characteristics of the coil, including length and index of refraction of the coil optical waveguide. These characteristics may vary with changes in environment, e.g., temperature, thereby causing changes in the eigenfrequency. Variations in the modulation frequency from the coil eigenfrequency cause errors in the measured rotation rate signal which may render the FOG unsuitable for use in high accuracy applications.

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Disclosure of Invention

An object of the present invention is the provision of a fiber optic rotation sensor having a phase modulator whose frequency is controlled to that of the

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coil eigenfrequency so as to reduce errors in rotation rate measurement.

According to the present invention, a fiber optic rotation sensor having a pair of light waves counter-
5 propagating in a loop includes a modulator driven by a signal at the loop eigenfrequency, upon exiting the loop the waves are combined into a light intensity signal which is sensed, the sensed signal including a component typically in a quadrature (ninety degree) phase relationship with the rotation rate
10 component, the magnitude of the quadrature component being proportional to any deviations in the modulator driving frequency from the loop eigenfrequency, the magnitude of the quadrature component used in feedback fashion to control the frequency of the modulator driving signal at the eigenfrequency
15 by driving the quadrature component to zero magnitude, thereby compensating for any deviations in the modulator driving signal frequency from the loop eigenfrequency.

In accordance with the present invention, there is provided a fiber optic rotation sensor having an optical
20 waveguide loop (46) having a loop transit time for a light wave to travel through said loop (46) for a present particular environmental condition of said loop, means (12, 31) for providing a pair of light waves counter-propagating in said loop (46), signal generator means (63) having a frequency
25 control input (116) for generating a modulation signal phase modulation means (57) for modulating said light waves in response to said modulation signal, means (31) for combining said light waves into an optical output signal, and means (52, 67) for detecting said optical output signal characterized by:
30 quadrature detection means (111, 106) for synchronously detecting a quadrature component on said output signal and providing a quadrature signal having a magnitude and a sign that indicates a deviation of frequency of said modulation signal from an odd integer multiple of a loop eigenfrequency,

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wherein the loop eigenfrequency is equal to one-half of the reciprocal of said loop transit time, and for converting the magnitude and sign of said quadrature signal into a frequency adjust signal which is provided to the frequency control input
5 (116) such that the frequency of said modulation frequency is adjusted so as to reduce the magnitude of said quadrature signal close to zero and in turn result in the frequency of said modulation signal being approximately equal to an odd integer multiple of the loop eigenfrequency, for said loop
10 having particular physical characteristics.

The present invention has utility in providing for servo control of the modulation frequency at the loop eigenfrequency. This allows the FOG to provide a more accurate indication of rotation rate over wide variations in
15 environment. Such operation also reduces potential errors associated with spurious optical intensity modulations in the phase modulator and with optical backscatter in the fiber coil.

The foregoing and other objects and advantages of the present invention will become more apparent in the light of the
20 following detailed description of an exemplary embodiment thereof, as illustrated in the accompanying drawing.

Brief Description of the Drawing

Fig. 1 is a schematic drawing of a fiber optic rotation sensor without the apparatus of the present invention therein;

5 Fig. 2 is a graph of the intensity of an optical output signal in the sensor of Fig. 1 as a function of a rotationally induced phase difference;

Fig. 3 is a graph of phase difference versus time time between a pair of counter-propagating waves in the
10 sensor of Fig. 1;

Fig. 4 is a graph illustrating the effect of phase modulation upon the intensity of an optical output signal in the sensor of Fig. 1, with the sensor at rest;

Fig. 5 is a graph illustrating the effect of phase
15 modulation upon the intensity of the optical output signal in the sensor of Fig. 1 with sensor rotation; and

Fig. 6 is a schematic drawing of the sensor of Fig. 1 with the apparatus of the present invention implemented therein.

20 Best Mode For Carrying Out The Invention

Fig. 1 illustrates a fiber optic rotation sensor, typically a fiber optic gyroscope (FOG) 10, having a light source 12, e.g., a laser diode or super luminescent diode, coupled to a length of a first
25 optical fiber 13. The fiber 13 is preferably a single-mode, high birefringence optical fiber, although non-birefringent fiber may be used. Light from the source 12 is optically coupled to an end of the first fiber 13 to maximize the amount of light entering
30 therein.

The first fiber 13 passes through a beamsplitter (directional optical coupler) 15 to direct light to an

integrated optical (IO) device 16. The coupler 15 may be fabricated using either the known fusion elongation method or the known mechanical polishing method.

5 The first fiber 13 enters the coupler 15 at a first port 20 and exits through a second port 21, and couples light to a second optical fiber 22 which enters the coupler at a third port 23 and exits through a fourth port 24. The second fiber 22 may be coupled at the fourth port 24 to a non-reflective termination 26, e.g., a light-absorbing terminator or a power monitoring system. Light entering 10 the first port 20 is split into two waves which may be of approximately equal intensity. One wave propagates into the second fiber 22 and exits at the fourth port 24. The other wave propagates in the first fiber and exits through 15 the second port 21.

Light exiting the second port 21 is optically coupled to a first port 30 of the IO device 16, in accordance with, e.g., commonly owned U.S. Patent No. 4,871,226 to Courtney et al. The IO device 16 comprises a Y-shaped optical 20 waveguide 31. The light is split into two substantially equal waves which exit the device 16 at second and third ports 33,34.

A third optical fiber 45 is wound into a Sagnac sensing loop 46. The fiber 45 typically comprises a 25 single-mode fiber, but may be a multi-mode fiber if desired. The fiber 45 is optically coupled to the second and third ports 33,34 of the IO device in a similar manner as described hereinbefore with reference to the first port

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30. The two waves exiting the IO device via the second and third ports 33,34 counter-propagate in the loop 46. The loop 46 may

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comprise a plurality of turns of optical fiber wound, e.g., on a cylindrical spool.

After traversing the loop 46, the waves re-enter the IO device 16 via the second and third ports 33, 34, and are recombined by the waveguide 31. The recombined waves exit the IO device 16 via the first port 30, and propagate in the first fiber 13 to the coupler second port 21. The light is then split into two waves which may be of approximately equal intensity. One wave propagates in the first fiber 13, exits through the first port 20, and passes through, or is absorbed by the source 12. The other wave propagates in the second fiber 22 and exits through the third port 23 to a photodetector 52, e.g., a photodiode. The photodetector provides an electrical signal proportional to the intensity of the optical signal at the third port 23, this optical signal representing the optical output signal of the FOG.

Preferably, a polarizer 55 may be formed on the first fiber 13 between the coupler 15 and the IO device 16. The polarizer 55 acts as a single-polarization filter, allowing light of one polarization mode to propagate therethrough while preventing light of an orthogonal polarization mode from propagating therethrough.

The IO device 16 also includes a phase modulator 57 comprising a pair of electrodes 58 fabricated using known techniques on a leg 61 of the waveguide 31 adjacent to the second port 33. The modulator 57 is driven by a signal on a line 62 at a modulation frequency by a known AC signal generator 63.

The generator output on the line 62 is also fed as a reference signal to a known lock-in amplifier 67. The

amplifier 67 also receives the electrical signal from the photodetector 52 on a line 68. The reference signal enables the amplifier 67 to synchronously detect the photodetector signal on the line 68 at the modulation
5 frequency. More specifically, the amplifier detects the first harmonic component of the intensity variations of the optical output signal on the line 22 while blocking all other harmonics of the modulation frequency. In particular, the amplifier detects the in-phase portion
10 of the first harmonic component, i.e., the portion which is in phase with the reference signal on the line 62. The magnitude of this in-phase first harmonic component of the optical output signal is proportional, through a certain operating range, to the rotation rate of the FOG
15 10. The amplifier 67 outputs a signal on a line 69 which is proportional to the first harmonic component, and thus provides a direct indication of the rotation rate.

If the FOG is operated with zero modulation
20 frequency, i.e., the signal generator 63 inoperative, the intensity, I_0 , of the optical output signal on the line 22 is a cosine function of the Sagnac phase difference, ϕ_R , between the counter-propagating waves as given by:

$$25 \quad I_0 = I_1 + I_2 + 2(I_1 I_2)^{\frac{1}{2}} \cos(\phi_R) \quad (\text{eq. 1})$$

where: I_1 and I_2 are the individual intensities of the counter-propagating waves.

Fig. 2 illustrates a curve 70 of the relationship
of equation 1. As can be seen, I_0 is a maximum when the
30 phase difference is zero. Also, rotation-induced phase differences between the waves cause I_0 to vary

symmetrically about the vertical axis. The intensity of the optical output signal is relatively insensitive to small changes in phase difference.

In Fig. 3, the counter-propagating waves modulated 180° out of phase from each other are illustrated by sinusoidal curves 75,76. Use of a modulation frequency which provides such 180° phase difference is desirable since it eliminates modulator-induced amplitude modulation in the optical output signal and it maximizes the phase difference between the counter-propagating waves.

In order to produce the 180° phase relationship between the counter-propagating waves, the modulation frequency is set at some odd integer multiple of the loop eigenfrequency, f_e , which is given by:

$$f_e = 1/2\tau = c/2nL \quad (\text{eq. 2})$$

where: τ is the loop transit time, c is the speed of light in a vacuum; n is the index of refraction of the loop optical fiber; and L is the length of the loop optical fiber.

With a modulation frequency of f_e , the phase difference, ϕ_1 , between the modulated waves 75,76 is illustrated in Fig. 3 by a sinusoidal curve 78. The curve 78 is obtained by subtracting the curves representing the counter-propagating waves, i.e., curve 75 - curve 76.

Modulation-induced phase differences, ϕ_1 , in the waves are indistinguishable from rotationally-induced Sagnac phase differences, ϕ_R . The intensity of the optical output signal on the line 22 is therefore a

function of the total phase difference, Φ_T , between the waves as given by:

$$I_o = I_1 + I_2 + 2(I_1 I_2)^{1/2} \cos(\Phi_T) \quad (\text{eq. 3})$$

where:

$$\Phi_T = \Phi_R + \Phi_1 \quad (\text{eq. 4})$$

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Illustrated in Fig. 4 is the effect of the modulator-induced phase difference, Φ_1 , on the optical output signal intensity, I_o . A cosine curve 79 illustrates the relationship of equation 3. When the relative phase angle between the waves is zero, the intensity of the combined waves is a maximum. When the relative phase between the waves is nonzero, the optical output signal has a lower intensity depending upon the magnitude of the phase difference Φ_T . The intensity continues to decrease with increasing Φ_T until the relative phase difference is either plus or minus 180°, at which point the two counter-propagating waves destructively interfere and the intensity is zero.

In the absence of FOG rotation, the only component of total phase difference, Φ_T , in equation 3 is the modulator-induced phase difference Φ_1 , as illustrated by curve 78. The modulation-induced phase difference curve 78 causes the optical output signal intensity at the detector to vary as illustrated in curve 88. The curve 88 is obtained by translating the points on the curve 78 onto the curve 79. Curve 78 represents the instantaneous phase difference between the counter-propagating waves, while curve 88 represents the resulting intensity of the optical output signal for

that particular instantaneous phase difference. The translation of the curve 78 through the curve 79 is symmetrical about the vertical axis of the curve 79, so that the optical intensity measured by the detector 52 varies periodically at a frequency equal to the second harmonic of the modulating frequency, as illustrated by the curve 88.

As described hereinbefore, the amplifier 67 is synchronized to detect only the in-phase portion of the first harmonic of the optical output signal on the line 22. But since the detector output signal is at the second harmonic of the modulation frequency, (curve 88), the output signal on the line 69 from the amplifier 67 will be zero, indicating zero rotation.

When the loop 46 is rotated, the phase of the counter-propagating waves is shifted per the Sagnac effect. The Sagnac phase shift both provides a constant phase difference ϕ_R for a constant loop rotation velocity and adds to the modulation-induced phase shift ϕ_1 so that the entire curve 78 is translated in phase from the zero rotation position shown in Fig. 4, by an amount equal to ϕ_R , as illustrated in Fig. 5. This causes the optical output signal to vary non-symmetrically along the curve 79 between the points 84 and 85, which in turn produces an optical output signal as illustrated by curve 90.

The optical output signal 90 has a first harmonic component as illustrated in phantom by sinusoidal curve 92. Curve 92 is in phase with the reference signal on the line 62 as well as the phase modulation curve 78, and its RMS value is proportional to the sine of the rotationally induced Sagnac phase difference ϕ_R . Since the amplifier 67 synchronously detects in-phase signals

having the fundamental frequency of the modulator 57, the amplifier output on the line 69 is proportional to the RMS value of the curve 92. As described hereinbefore, this signal can be used to indicate the FOG rotation rate.

Fig. 5 illustrates the optical output signal 90 for one direction of rotation of the loop. However, if the loop is rotated in the opposite direction at an equal velocity, the optical output signal is similar to that illustrated in Fig. 5, except for a translation such that the curve 90 is shifted 180° from its position in Fig. 5. The amplifier 67 detects this 180° phase difference for the optical output signal by comparing the phase of the first harmonic curve 92 with the phase of the reference signal from the generator 63 to determine whether the rotation of the loop is clockwise or counter-clockwise. Depending on the direction of rotation, the amplifier may provide as output either a positive or negative signal. Regardless of the direction of rotation, the magnitude of the signal is the same for equal rates of rotation of the loop.

The rotation rate sensing system described hereinbefore with reference to Figs. 1-5 is effective within a certain range of rotational velocities for the loop 46 for which the output of the amplifier 67 varies approximately linearly with rotation rate. The effective range of the FOG can be extended, if desired, by using known feedback techniques, e.g., comprising serrodyne phase modulation, to null the Sagnac phase shifts.

Whether or not a range extending technique is used, the accuracy of rotation measurement may be reduced when the modulation frequency is not equal to the loop

eigenfrequency or an odd integer multiple thereof. This is because certain errors, such as some caused by optical backscatter, cancel only if the modulation frequency equals the eigenfrequency, and because FOG
5 system imperfections may permit the in-phase amplifier
67 to respond spuriously to quadrature (90 degrees out of phase) signals associated with deviations from the eigenfrequency, as described hereinafter.

Typically, the modulator 57 may cause spurious
10 intensity modulation, as well as the intended phase modulation, of the waves passing therethrough. If the modulation frequency is equal to the loop eigenfrequency, the resultant intensity modulations seen in the counter-propagating waves exiting the loop 46 are
15 out of phase and cancel each other.

However, if the modulation frequency differs slightly from the eigenfrequency, the cancellation is incomplete, and photodetector 52 sees an intensity modulation component which is proportional to the
20 deviation from the eigenfrequency and which is substantially in quadrature with the phase reference signal on the line 62, and with the rotation induced curve 92, as illustrated by curve 100 in Fig. 4. The resulting quadrature signal on the line 68 may
25 contribute spuriously to the output of the in-phase amplifier 67 if, e.g., the amplifier phase circuits drift or are misadjusted.

In some cases, it may actually be desirable to modify the modulator 57 to increase the magnitude of the
30 spurious intensity modulation, and thus the quadrature signal. This is because the present invention relies on the presence of this signal to sense and null any deviations from the eigenfrequency, in order, e.g., to

reduce the aforementioned backscatter errors. When the frequency deviations are nulled, the quadrature component, whether spuriously or intentionally introduced, is automatically nulled, thereby preventing it from adversely affecting the output of the amplifier
5 67.

The modulator 57 may typically be modified by shortening the length of the electrodes 58 on the IO device. The magnitude of the voltage signal on the line
10 62 from the generator 63 is then increased so as to increase the magnitude of the spurious intensity modulation, and thus the quadrature signal. The increased voltage has marginal effect on the resulting phase modulation of the waves caused by the modulator.

15 In the alternative, Fig. 1 illustrates a separate intensity modulator 102 comprising a pair of electrodes 104 fabricated on the IO device on the leg 61 of the waveguide 31. The modulator 102 is driven by a signal on a line 105 from an amplifier 106 which provides the
20 proper voltage amplification of the generator signal on the line 62. In a similar manner, the effect of the intensity modulator is to increase the magnitude of the spurious intensity modulation, and thus the quadrature signal.

25 In Fig. 6, the FOG 10 of Fig. 1 is illustrated with the modulation frequency control apparatus of the present invention implemented therein. The curves in Figs. 2-5 remain valid in illustrating the operation of the FOG of Fig. 6. The electrical signal on the line 68
30 from the detector 52 is fed to a second (quadrature) amplifier 111, which may be similar to the first lock-in amplifier. In a manner similar to Fig. 1, the generator provides the synchronizing reference signal on the line

62 to the quadrature amplifier 111 to enable the quadrature amplifier to synchronously detect a quadrature component of the detector signal on the line 68 at the reference signal frequency, e.g., the loop eigenfrequency. The reference signal also enables the first lock-in amplifier 67 to detect the in-phase component (i.e., desired rotational rate information) of the detector signal at the same frequency.

The quadrature amplifier provides a signal on a line 116 to the generator 63, the signal being indicative of the magnitude and sign of the quadrature output signal. The generator is responsive thereto in adjusting the frequency of the modulating signal on the line 62 to the phase modulator to equal that of the eigenfrequency. In this way, the generator is being used as a well-known voltage controlled oscillator (VCO). The resulting modulation of the counter-propagating waves makes the intensity of the quadrature output signal (curve 100) equal to zero, indicating that the frequency of the modulation signal on the line 62 equals the current value of the loop eigenfrequency, thereby compensating for dynamic variations in the loop eigenfrequency due to environmental changes.

A FOG having the apparatus of the present invention implemented therein provides a more accurate indication of rotation rate over wide variations in environment over known prior art FOGs. Such operation also reduces potential errors associated with spurious optical intensity modulations in the phase modulator and with optical backscatter in the fiber coil.

As described, the apparatus of the present invention is implemented in a fiber optic gyroscope.

However, it is to be understood that the present invention may be implemented, if desired, in other types of interferometers in a manner which should be apparent to one of ordinary skill in the art in light of the teachings herein.

As illustrated, the IO device 16 is described as having the Y-shaped waveguide 31 and phase modulator 57 fabricated thereon. However, the coupler 15 and polarizer 55 may also be fabricated thereon if desired. Such fabrication eliminates a portion of the optical fibers 13,22. Also, the source 12 and detector 52 may be disposed to abut the IO device 16 directly, thereby eliminating the first and second fibers 13,22 altogether. Further, the coupler 15 is illustrated as having the fiber 13,22 passing therethrough. However, the coupler 15 may instead be such that end surfaces of the fibers interface at the ports 20,21,22,23 thereof.

All of the foregoing changes are irrelevant; it suffices for the present invention that a fiber optic rotation sensor having a pair of light waves counter-propagating in a loop includes a modulator driven by a signal at the loop eigenfrequency, upon exiting the loop the waves are combined into a light intensity signal which is sensed, the sensed signal including an component typically in a quadrature (ninety degree) phase relationship with the rotation rate component, the magnitude of the quadrature component being proportional to any deviations in the modulator driving frequency from the loop eigenfrequency, the magnitude of the quadrature component being used in feedback fashion to control the frequency of the modulator driving signal at the eigenfrequency by driving the quadrature component to zero magnitude,

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thereby compensating for any deviations in the modulator driving signal frequency from the loop eigenfrequency.

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CLAIMS:

1. A fiber optic rotation sensor having an optical waveguide loop (46) having a loop transit time for a light wave to travel through said loop (46) for a present particular environmental condition of said loop, means (12, 31) for providing a pair of light waves counter-propagating in said loop (46), signal generator means (63) having a frequency control input (116) for generating a modulation signal phase modulation means (57) for modulating said light waves in response to said modulation signal, means (31) for combining said light waves into an optical output signal, and means (52, 67) for detecting said optical output signal characterized by:

quadrature detection means (111, 106) for synchronously detecting a quadrature component on said output signal and providing a quadrature signal having a magnitude and a sign that indicates a deviation of frequency of said modulation signal from an odd integer multiple of a loop eigenfrequency, wherein the loop eigenfrequency is equal to one-half of the reciprocal of said loop transit time, and for converting the magnitude and sign of said quadrature signal into a frequency adjust signal which is provided to the frequency control input (116) such that the frequency of said modulation frequency is adjusted so as to reduce the magnitude of said quadrature signal close to zero and in turn result in the frequency of said modulation signal being approximately equal to an odd integer multiple of the loop eigenfrequency, for said loop having particular physical characteristics.

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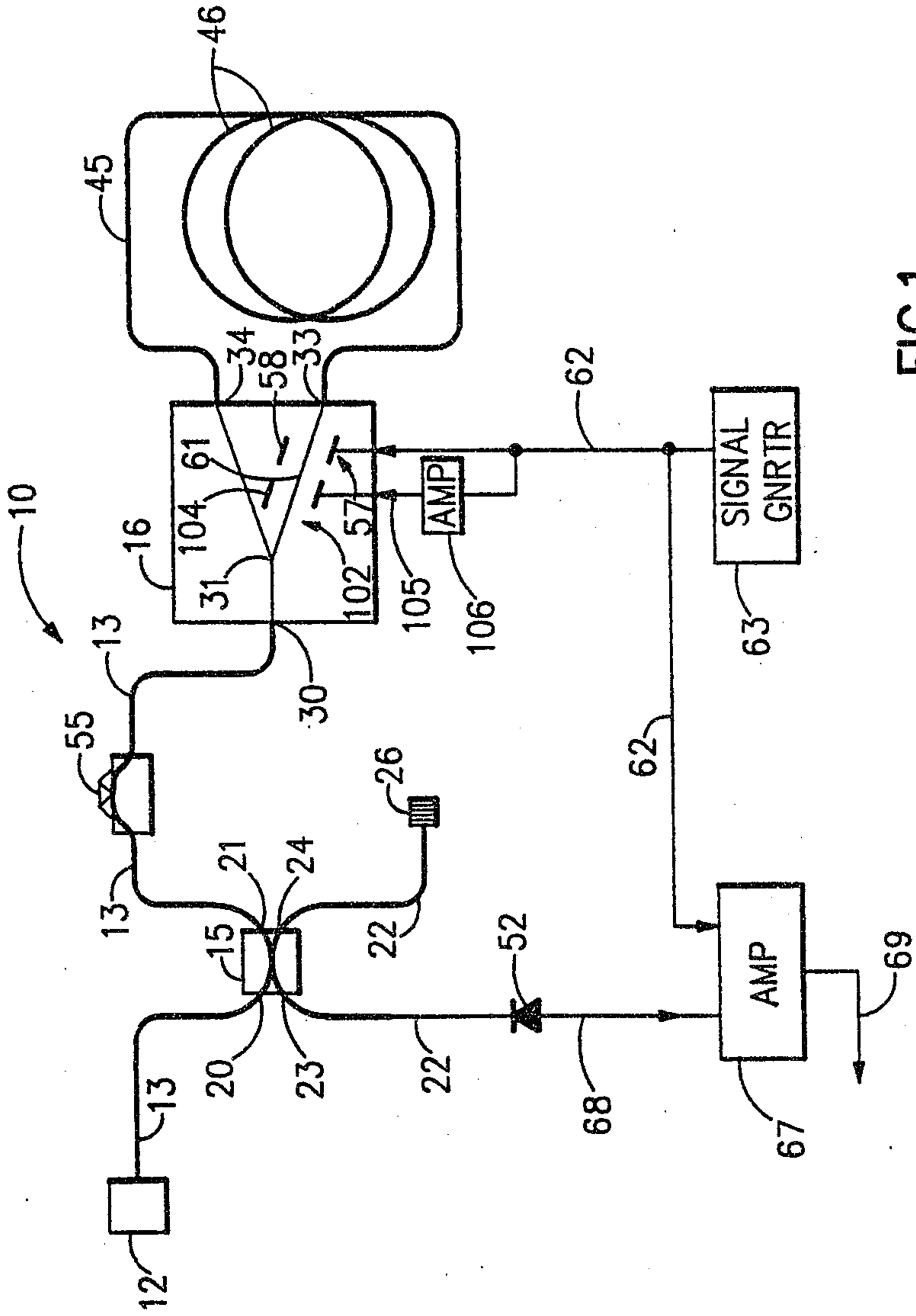


FIG.1
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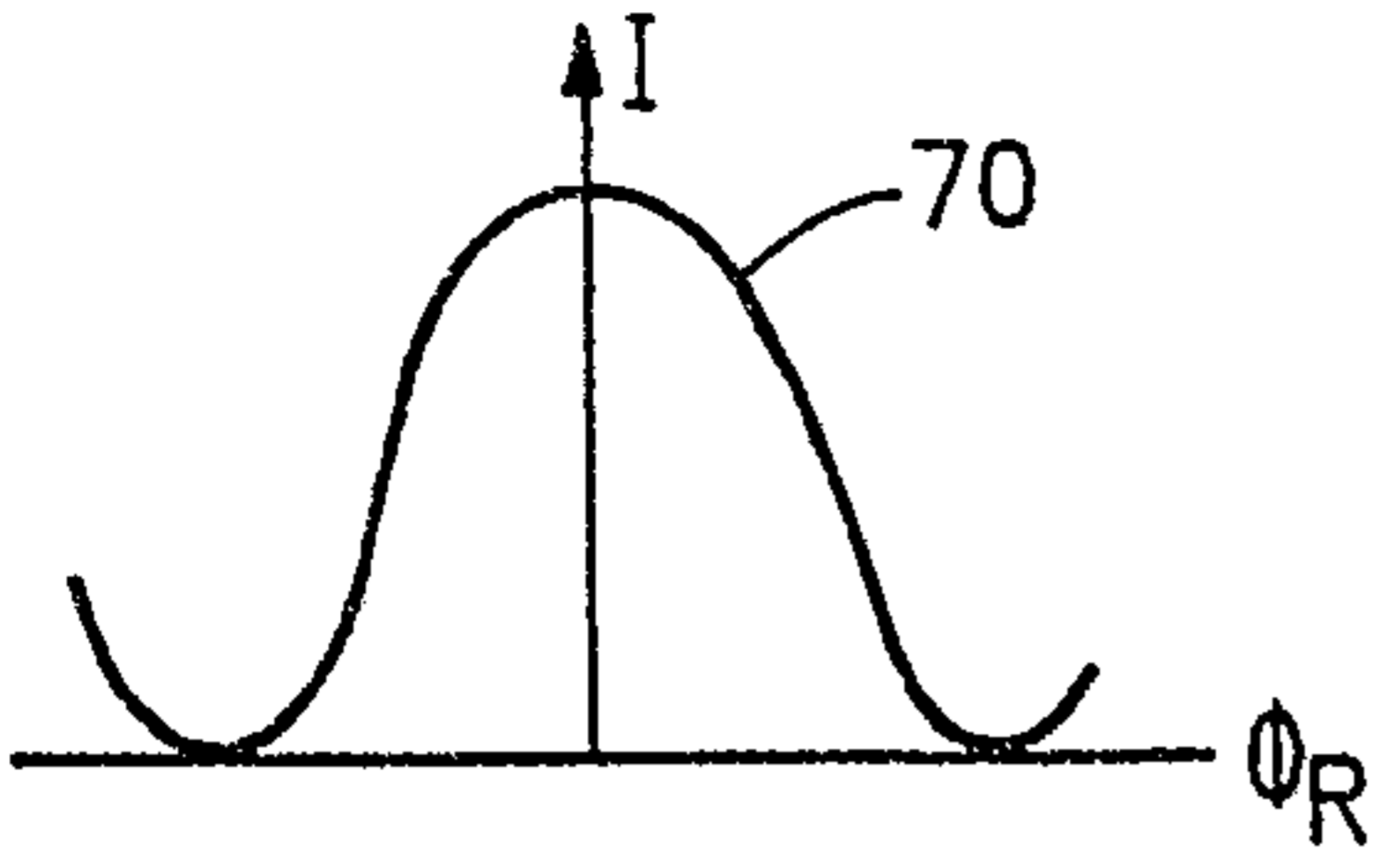


FIG. 2

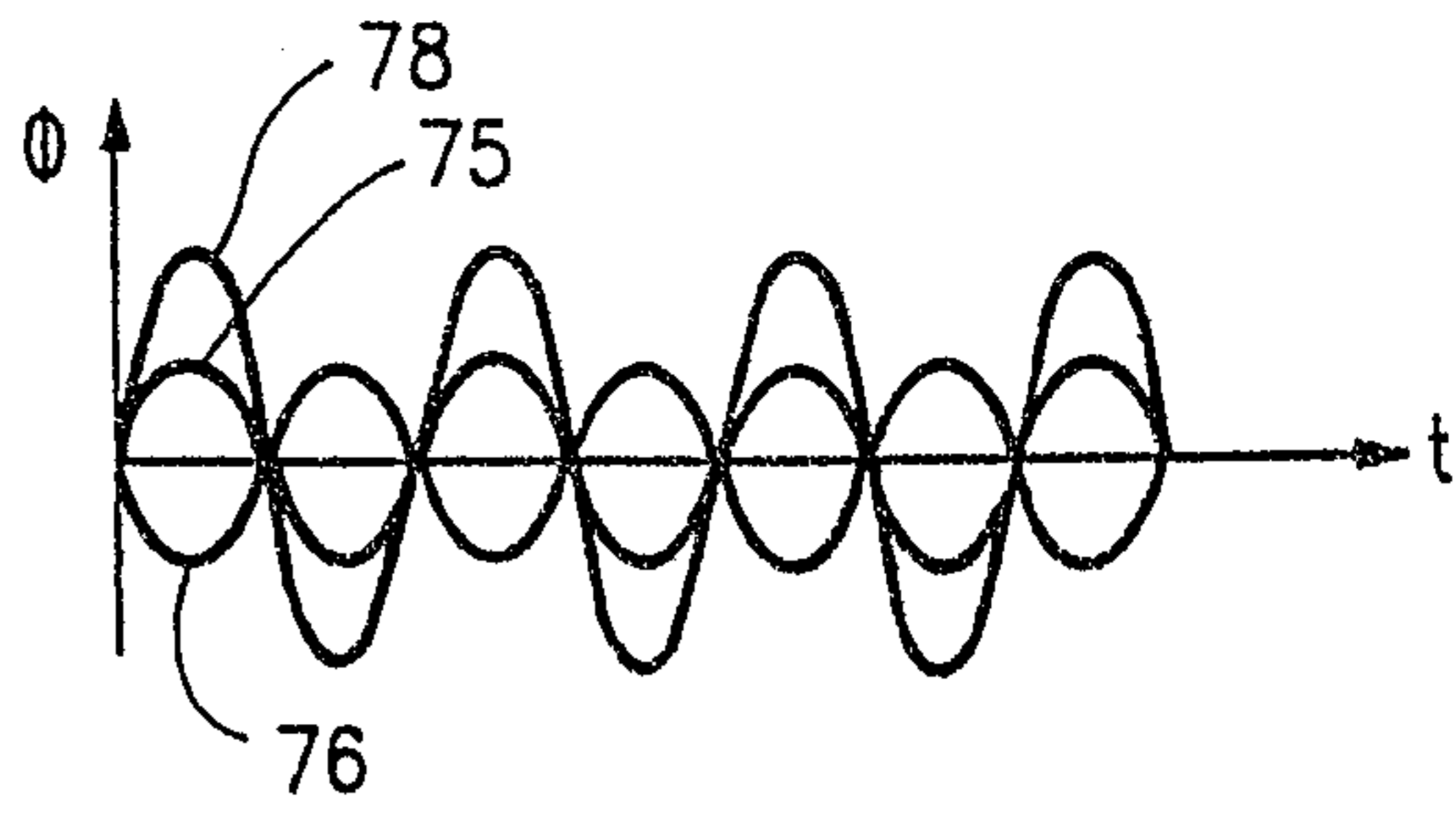


FIG. 3

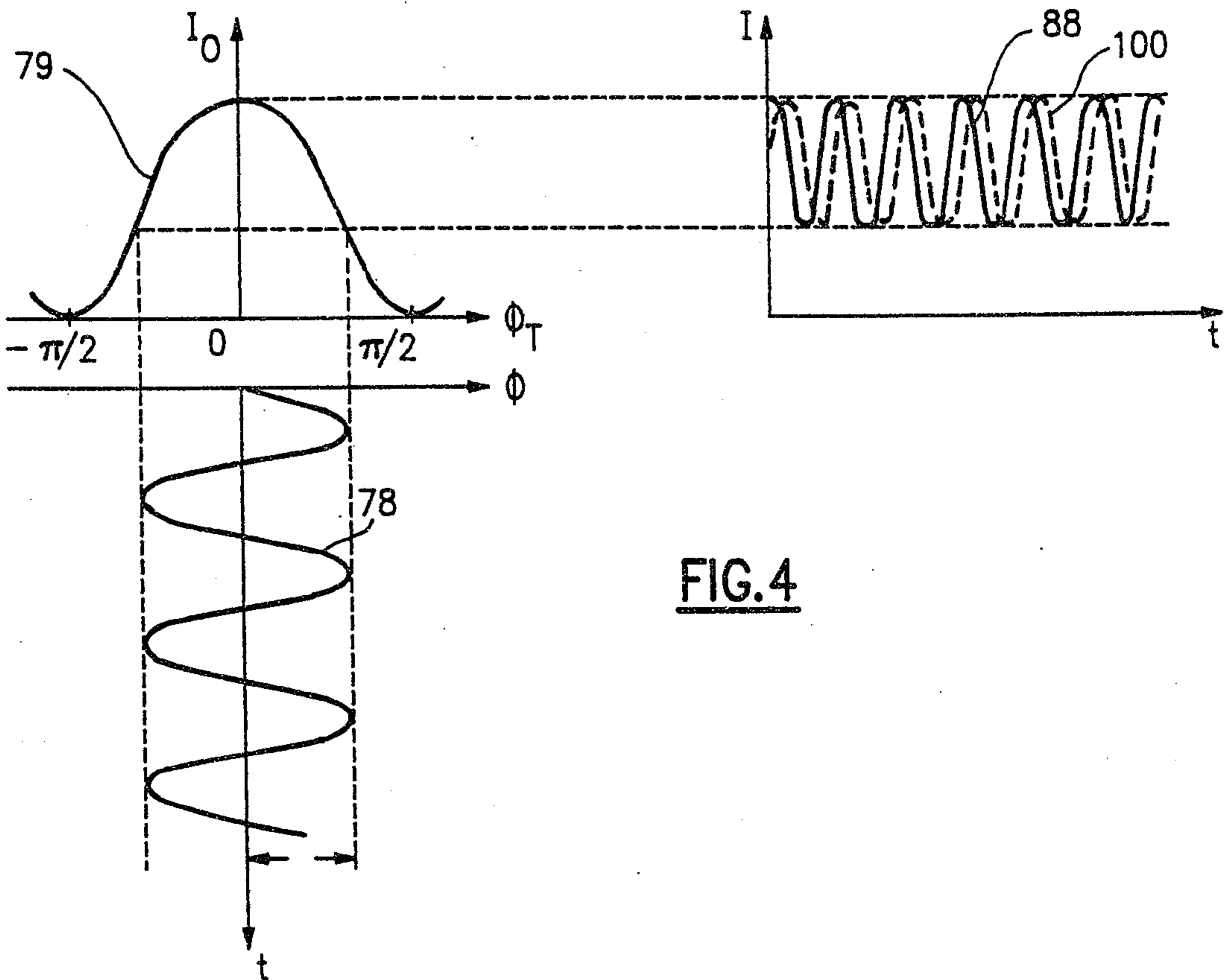


FIG. 4

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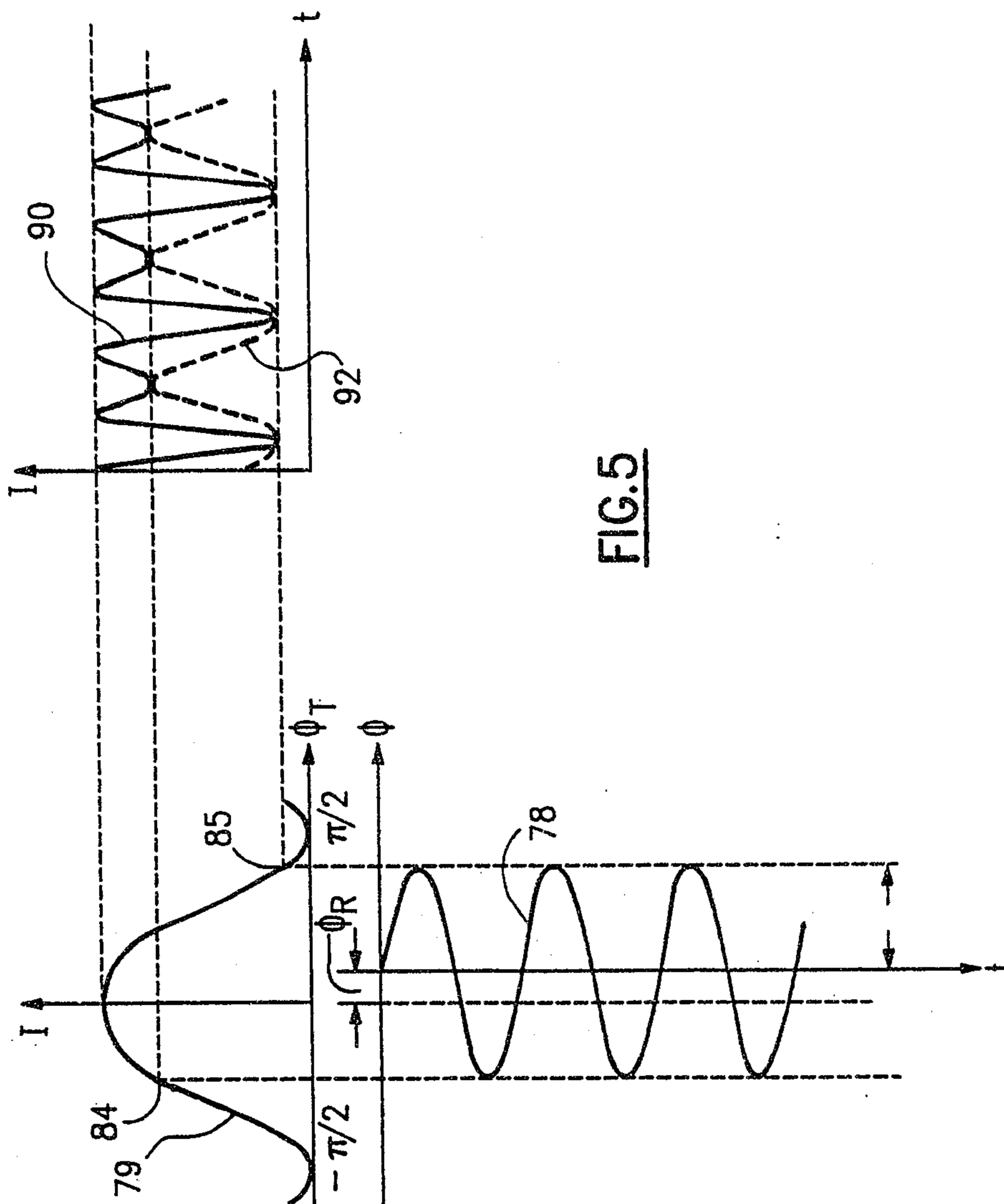


FIG. 5

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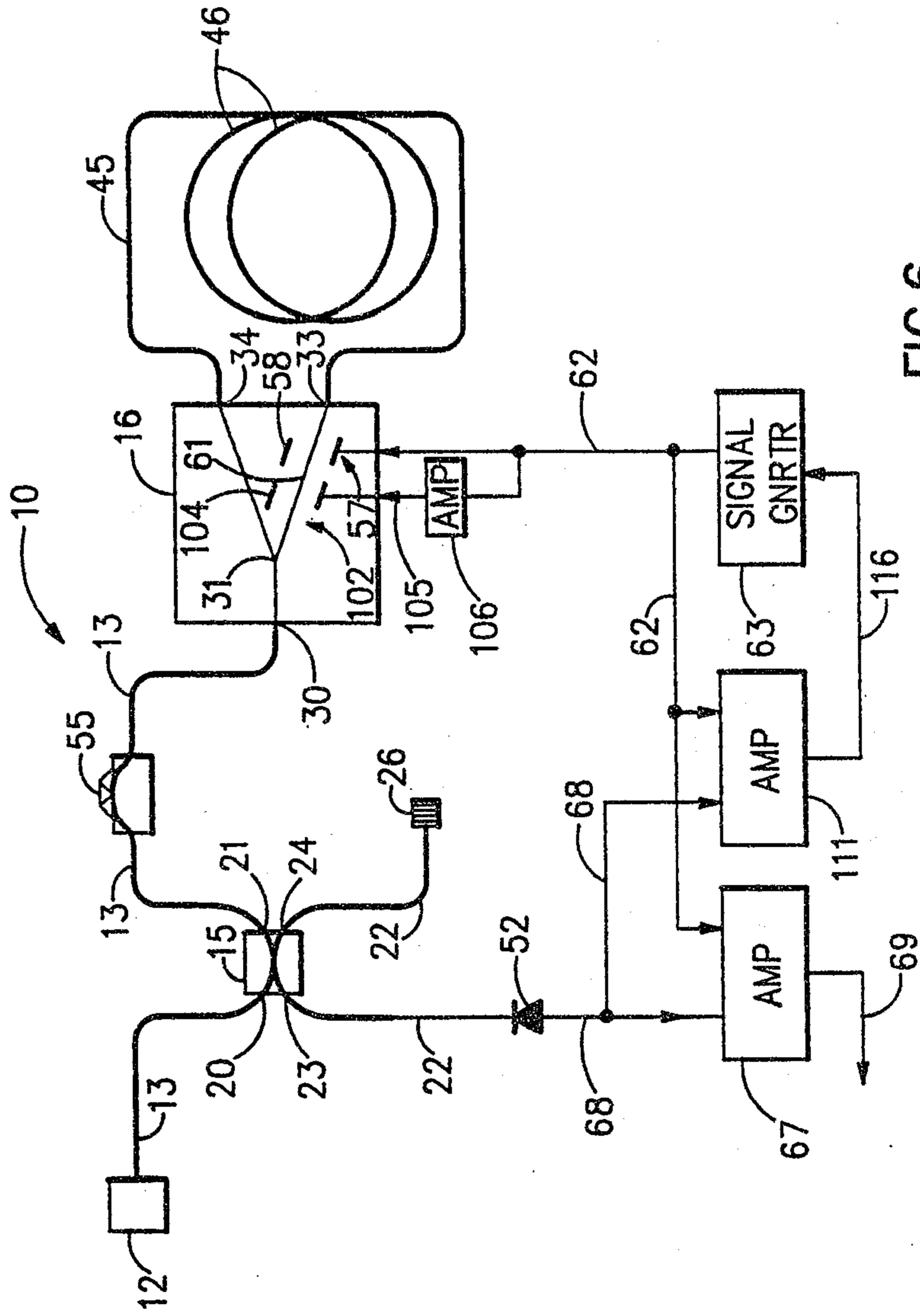


FIG. 6

