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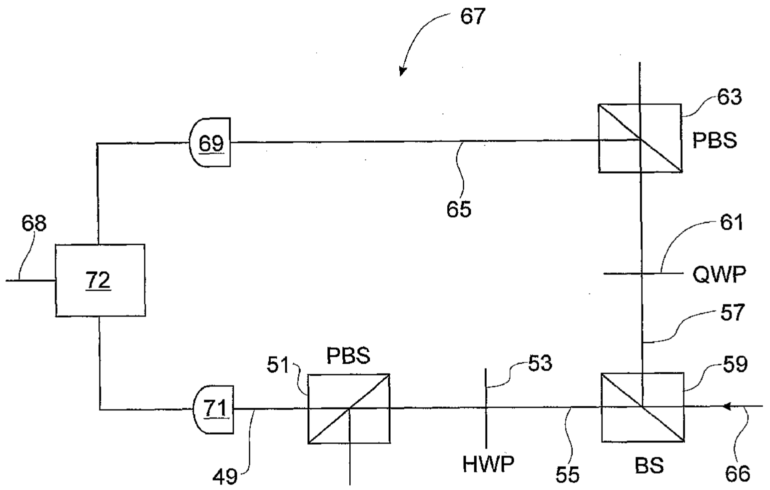
(54) Title: METHOD AND APPARATUS FOR DETECTING FREQUENCY CHANGE OF ELECTROMAGNETIC RADIATION



(57) Abstract: In one embodiment the invention provides a laser locking apparatus including a laser (36) that generates a beam (44) that is received by a polarising beam splitter (46). Beam splitter (46) produces a vertically polarised beam (60) and horizontally polarised beam (48). Beam (60) passes, via mirror (52), through a holographic plate (54) that transforms the spatial mode of beam (60) from a TEM_{00} mode to TEM_{01}, mode in beam (62). Horizontally polarized beam (48), which is in TEM_{00} spatial mode, is combined, via mirror (50), with beam (62) by polarising combiner (56). Combined beam (64) is reflected by empty cavity (58) to generate a reflected beam (66). Cavity (58) is dimensioned so that at a desired locking frequency the $HTEM_{00}$mode component is resonant with the cavity. Detector (67) receives reflected beam (66) and determines the phase-shift between the horizontal and vertical components of the light and hence the shift between the TEM_{00} andTEM_{01} modes. Detector (67) generates a suitable error signal if the phase shift is other than half a wavelength and applies the error signal via cable (68) to control laser (36) back towards locking frequency.

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METHOD AND APPARATUS FOR DETECTING FREQUENCY CHANGE OF ELECTROMAGNETIC RADIATION

FIELD OF THE INVENTION

The present invention relates to methods and apparatus for detecting phase-shift and associated frequency change or "drift" of electromagnetic radiation. The present invention finds particular application where accurate frequency stabilisation of an electromagnetic radiation source, such as a laser, is required.

BACKGROUND TO THE INVENTION

Frequency stabilisation or "locking" of electromagnetic radiation sources became necessary with the development of RF communications at the beginning of the twentieth century. During World War II, R. Pound made the first major advance in frequency locking with a modulated technique that enabled successful development and refinement of RADAR systems.

Within a short time of the development of the laser in the 1960's, the first application of frequency locking to a source at optical frequencies to be developed was the modulated method of "dither locking", adapted from atomic spectroscopy. The dither locking technique was rapidly adopted, in part because it was straightforward to apply with then existing techniques and equipment.

In 1983, with the advent of high frequency optical modulators, Pound's technique was finally adapted to the optical frequency range. The Pound technique involves several optical frequencies and so is complex to implement so that its application is largely restricted to the laboratory.

In US Patent 4,451,923 to Hansch and Couillaud there is described an unmodulated technique for laser locking that involves detecting the amplitude difference between orthogonal polarisations of laser light due to interaction of the light with a resonant cavity. The Hansch-Couillaud system is particularly suitable for use in optically anisotropic systems, including dye lasers and frequency converters and is simple to implement, as it does not involve modulation.

While the Hansch-Couillaud system is more readily implemented than previous approaches, which required modulation of light sources, the characteristics of the error signal that it generates, and which is used to lock the laser frequency, are less than optimal.

Recently another frequency locking approach has been described in a paper by D. Shaddock, M. Gray, and D. McClelland, Opt. Lett 24, 1499 (1999). In that paper "tilt-locking" is described. Tilt locking involves the use of an empty cavity, i.e. one with no polarisation dependence. Due to Guoy phase-shift an empty cavity may have different resonant frequencies for different spatial mode components in an incident light field, namely the TEM_{00} and TEM_{01} modes. The tilt-locking technique is based on the principle that if there were no relative phase-shift, the two lobes of the TEM_{01} component would experience the same interference with the TEM_{00} mode and so have the same resultant intensity. Conversely, if there were a relative phase-shift, one lobe of the TEM_{01} mode would experience constructive interference, and the other destructive so that one lobe would have a greater intensity than the other. By measuring the intensity of the two lobes of the reflected field on a split detector and differencing them an error signal is generated. Although the tilt-locking system provides an improvement over previous prior-art techniques it would be desirable if the characteristics of the error signal it generates could be improved upon.

It is an object of the present invention to provide a method and apparatus for analysing electromagnetic radiation that is simple to implement and which may be used to lock the frequency of a radiation source, such as a laser.

SUMMARY OF THE INVENTION

According to a first aspect of the present invention there is provided an apparatus for detecting frequency drift of electromagnetic radiation, the apparatus comprising:

phase shifting means for selectively imparting differing frequency dependent phase shifts to respective components of the electromagnetic radiation; and

phase detection means responsive to the phase shifting means for generating a control signal dependent on the phase shifts.

In a preferred embodiment of the present invention the apparatus includes a means for generating the electromagnetic radiation.

Preferably the means for generating the electromagnetic radiation is responsive to the control signal and so is frequency locked.

Alternatively the phase shifting means may be responsive to the control signal. For example, the phase shifting means may comprise a resonant cavity, the active length of which may be adjusted in response to the control signal.

The phase detection means may be arranged to detect a relative phase shift between orthogonally, for example horizontally and vertically, polarised components of the electromagnetic radiation.

Alternatively the phase detection means may be arranged to a detect a relative phase shift between orthogonal spatial mode components of the electromagnetic radiation.

The means for generating the electromagnetic radiation may, for example, be any one of: a RF oscillator (including UHF, VHF and microwave frequency oscillators), an optical frequency source (such as a laser).

The phase shifting means may be, for example, any one of: an antenna, a microwave reflector, a resonant cavity.

Where the means for generating the electromagnetic radiation generates optical frequency radiation then the phase detection means may include optical elements, such as polarising beam splitters and/or wave plates, for analysing the polarisation state of the electromagnetic radiation.

The phase detection means may further include a number of transducing means for transducing components of the electromagnetic radiation into corresponding electrical signals.

The phase detection means typically includes electronic processing circuitry. For example the phase detection means may include analogue circuitry or alternatively it may contain digital electronics including a digital processor for processing the signals from the transducing means in order to produce the control signal.

The control signal is typically either the relative phase shift, or its tangent, imparted by the cavity.

According to a further aspect of the present invention there is provided a laser locking assembly including:

a resonant cavity configured to impart differing frequency dependent phase shifts to respective components of a laser beam and to exhibit resonance for a particular component at a desired locking frequency;

a phase detector responsive to the resonant cavity and arranged to generate a control signal dependent upon relative phase shift between said components imparted by the cavity; and

a laser for generating the laser beam and responsive to the control signal for frequency stabilisation at the locking frequency.

In one embodiment the resonant cavity is anisotropic and is configured to impart the frequency dependent phase shift to orthogonal linearly polarised components of the laser beam. In that case the phase detector may be arranged to partially determine the polarisation state of light from the resonant cavity in order to produce the control signal.

Preferably the phase detector is a Stokes parameter detector. In that case the phase detector includes transducing means for detecting intensities of diagonal and right-circular polarised components of light respectively.

The transducing means may include photodetectors and wave plates.

The laser locking assembly may include a means for converting a portion of the laser beam into a spatial mode component that is orthogonal to the remainder of the beam. In that case the cavity may be empty and configured to selectively impart a frequency dependent phase shift to a particular one of said spatial mode components.

According to a further embodiment of the present invention there is provided an optical disk drive including a laser locking assembly as previously described.

According to a final aspect of the present invention, there is provided a method for detecting frequency drift of electromagnetic radiation including the steps of:

imparting differing phase shifts to respective components of the electromagnetic radiation depending on deviation of the frequency of the electromagnetic radiation from a centre frequency;

subsequently detecting a relative phase shift between said components; and

generating a control signal depending on the imparted relative phase shift detected.

In a preferred embodiment the step of imparting the phase shifts includes causing the electromagnetic radiation to interact with a resonant element of a type that exhibits a resonance for one component of said radiation at the centre frequency.

In a preferred embodiment the method includes a step of generating the electromagnetic radiation.

Preferably the electromagnetic radiation is generated in response to the control signal thereby frequency locking the electromagnetic radiation.

Further preferred features of the present invention will be described in the following detailed description which will refer to a number of figures as follows.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic diagram of an apparatus for detecting frequency drift of electromagnetic radiation according to an embodiment of the present invention.

Figure 2 is a schematic diagram of components within one of the modules of Figure 1.

Figure 3 is a graph including a plot of the theoretical relationship between error signal and deviation from locking frequency for the apparatus of Figure 1 for a dichroic cavity.

Figure 4 is a graph including a plot of the theoretical relationship between error signal and deviation from locking frequency for the apparatus of Figure 1 wherein the cavity is birefringent.

Figure 5 is a frequency locking arrangement according to an embodiment of the present invention.

Figure 6 is a frequency locking arrangement according to a further embodiment of the present invention.

Figure 6A is a block diagram of a detector of Figure 6.

Figure 7 is a graph including a plot of the theoretical relationship between error signal and deviation from locking frequency for the apparatus of Figure 6.

Figure 8 is a diagram of an apparatus for detecting frequency shift of electromagnetic radiation according to a further embodiment of the present invention.

Figure 9 is a schematic diagram of a optical disk drive according to a further embodiment of the present invention.

Detailed Description of Exemplary Embodiments

The present invention will be described predominantly in relation to optical frequencies and in particular in the context of laser physics. However, it will be realised that the invention also finds application in other electromagnetic frequency ranges. For example, as previously alluded to, the invention may find application in the microwave frequency range and also at lower frequencies.

With reference to Figure 1, an optical cavity 2 receives a beam of light E_i from light source 4. E_i may be decomposed into two orthogonal components which are orthogonally polarised and have a fixed phase relationship.

$$E_i = E_{i1}\hat{x}_1 + E_{i2}\hat{x}_2 \qquad (1)$$

Here E_{i1} and E_{i2} are complex amplitudes of the field components and $\hat{x}_1$ and $\hat{x}_2$ are orthogonal basis vectors. If $\hat{x}_1$ and $\hat{x}_2$ are chosen as horizontal and vertical basis vectors then a wave of plane polarised light may be represented as:

$$E = \begin{pmatrix} E_H \\ E_V \end{pmatrix} = \begin{pmatrix} A_H \\ A_V e^{i\phi} \end{pmatrix} e^{i(\omega t - kz)}, \quad (2)$$

where A_H and A_V are the amplitudes of the two field components, ω is the angular frequency of the light, t is time, $k=2\pi/\lambda$ is the wavenumber of the light, z is distance in the direction of propagation and ϕ is the phase difference between the two polarisations.

Referring again to Figure 1, cavity 2 is chosen so that it exhibits different resonant frequencies for the $\hat{x}_1$ and $\hat{x}_2$ field components. Accordingly, the $\hat{x}_1$ component may be chosen to be resonant at a predetermined "locking frequency". At the locking frequency the $\hat{x}_2$ component will be almost completely reflected. The reflected field from cavity 2 is defined as:

$$E_r = E_{i1}F_{r1}\hat{x}_1 + E_{i2}F_{r2}\hat{x}_2 \qquad (3)$$

Where F_{r1} and F_{r2} are the reflectances of cavity 2 for the $\hat{x}_1$ and $\hat{x}_2$ components respectively. If the frequency of the input beam is swept through the frequency at which resonance for $\hat{x}_1$ occurs, i.e. the "centre" or "locking" frequency then the $\hat{x}_1$ component of the reflected beam will experience a phase-shift relative to the $\hat{x}_2$ component. If the $\hat{x}_1$ component is chosen to be horizontally polarised (H) and the $\hat{x}_2$ component is chosen to be vertically polarised (V) then by measuring the S_2 and S_3 Stokes parameters of the reflected beam, the relative phase shift ϕ between the components may be determined and used as an error signal to indicate deviation of light source 4 from the centre frequency.

The relationship between the Stokes parameters and the relative phase-shift imparted by cavity 2 will now be explained. The Stokes parameters for the total field are well known, for example from M. Born and E. Wolf, *Principles of Optics* (Cambridge University Press, Cambridge 1999) 7th Ed. Expanding these using the definitions of E_H and E_V in equation 2, and applying Euler's formula, we find,

$$S_0 = A_H^2 + A_V^2, \quad \text{(4a)}$$

$$S_1 = A_H^2 - A_V^2, \quad \text{(4b)}$$

$$S_2 = 2(A_H A_V \cos\phi), \quad \text{(4c)}$$

$$S_3 = 2(A_H A_V \sin\phi), \quad \text{(4d)}$$

The Stokes parameters may be obtained by measurement of the intensity of the horizontal, diagonal and right-circular components of E. i.e.

$$S_i = 2I_i - I_0 \quad (i=0,1,2,3) \quad \text{(5)}$$

where I_i are the measured intensities, I_0 is the total light intensity and $i=1,2,3$ refer to the horizontal, diagonal and right-circular components of E respectively.

The expressions for S_2 and S_3 in equations 4 combine to yield the phase difference ϕ between E_H and E_V i.e.

$$\tan\phi = \frac{S_3}{S_2} \quad \text{(6)}$$

or equivalently

$$S_2 + iS_3 = 2A_H A_V e^{i\phi} \quad \text{(7)}$$

The phase difference ϕ between E_H and E_V, may be extracted from either of expressions (6) and (7). The relative intensities of the H and V polarised components have no effect on the value of the recovered phase, providing both are detectable. If one of the linearly polarised components is greater than the other, it contributes equally to both S_2 and S_3 and so, inspecting equations (5) and (6), we see that there is no net effect on ϕ. The limiting factors in choosing the intensities of the H and V components are the efficiency of the detectors and the detector noise.

In the embodiment of Figure 1 the determination of the phase-shift is performed by phase-shift analyser 6, the internal components of which are shown in Figure 2. Initially incoming beam E_r is split in two by a 50-50 beam splitter 8 into beams 12 and 14. Quarter beam plate 10 transforms left and right circular components of beam 12 into corresponding vertical and horizontal components of beam 24. Polarizing beam-splitter 21 splits beam 24 into separate horizontally and vertically polarised component beams 30 and 28 respectively. The intensity of the horizontally polarised beam 30 is detected by photodetector 33 which produces a corresponding electrical signal on cable 39. The intensity of the vertically polarised beam 28 is detected by photodetector 32 which produces a corresponding electrical signal on cable 37. The intensity signals are appropriately scaled and differenced by pre-processor 35, for example a suitably configured operational amplifier, to produce a signal corresponding to the S3 Stokes parameter.

Beam 14 from splitter 8 is incident upon a half wave plate 15 which transforms diagonal and anti-diagonal components in beam 14 into corresponding horizontal and vertical linearly polarized components of beam 16. Polarizing beam splitter 19 splits beam 16 into horizontally and vertically polarized component beams 18 and 17 respectively. The intensity of horizontally polarised beam 18 is detected by photodetector 20 to produce a corresponding electrical signal on cable 41. The intensity of the vertically polarised beam 17 is detected by photodetector 23 which produces a corresponding electrical signal on cable 43. The intensity signals on cables 41 and 43 are appropriately scaled and differenced by pre-processor 45 to produce a signal corresponding to the S2 Stokes parameter.

The S2 and S3 signals from pre-processors 35 and 45 are processed by processor 22 to generate an error signal on cable 34. If processor 22 is to obtain ϕ from equation 6 then it will include a fast digital processor and associated analog-to-digital converters to calculate the arctangent function. In that case pre-processors 35 and 45 may be implemented by processor 22. If a higher frequency response is required, equation 5 may prove amenable to an analogue sideband technique, allowing ϕ to be measured without having to directly calculate the arctangent. If a linear phase response is not required (e.g. as would be the case for frequency locking) then the signal provided by S_3/S_2, , i.e. $\tan\phi$, will indicate if there is a phase difference between the components and the direction of this phase-shift. In that case processor 22 may be readily implemented in analogue electronics. As will be explained, the error signal may be used to control a radiation source, such as a laser, in order to stabilise or frequency lock the source. Alternatively, radiation source 4 may be used as a frequency reference in which case the error signal from detector 6 might be used to stabilise cavity 2. For example, some cavities include a piezoelectric element for adjusting inter-cavity length.

It will now be explained that a system according to Figure 1 is theoretically capable of providing an error signal with characteristics that are an improvement over that provided by the prior Hansch-Couillaud technique. For a symmetric, confocal, two-mirror cavity, F_r may be shown to be:

$$Fr = r - \frac{t^2 r e^{-2\alpha L - i(\frac{4\pi n_c L}{\lambda_0} + \psi_{rt})}}{1 - r^2 e^{-2\alpha L - i(\frac{4\pi n_c L}{\lambda_0} + \psi_{rt})}} \qquad (8)$$

Where

r is the reflectance of the cavity mirrors

α is the absorption per unit length in the cavity

L is the cavity length

k is the wavenumber of the light in the cavity

Ψ_{rt} is the round trip Guoy phase-shift for the mode being analysed given by $\Psi_{rt}=(m+n+1)\pi/2$ where m and n are Hermite-Gauss mode numbers.

n_c is the effective refractive index for the cavity and λ_o is the free space wavelength of the light.

In the case where cavity 2 comprises a dichroic cavity the reflectances are given by

$$F_{rH}=F_r(\alpha=\alpha_o) \text{ and } F_{rV}=F_r(\alpha=\alpha_0+\alpha_d) \qquad (9)$$

where α_o is the cavity loss per unit length experienced by both components and α_d is the loss per unit length experienced only by the vertically polarised component due to dichroism.

Figure 3 is a graph showing plot of ϕ and $\tan\phi$ for various frequencies about the locking frequency of the cavity. Also shown on the graph is a plot depicting the corresponding error signal produced by the Hansch-Couillaud locking method. The inset graph of Figure 3 shows detuning plots over several free spectral ranges for the cavity. The plots in Figure 3 show that theoretically the error signal obtained by the embodiment of Figure 1 is significantly steeper than that of Hansch-Couillaud locking near the resonance frequency. In fact the orthogonal modes error signal is the cavity dispersion so that no steeper locking signal can be obtained with linear means. This is also seen in the steeper locking potentials for small detuning. The inset to Figure 3 shows the same error signals calculated for several free spectral ranges. The error responses generated by these two methods overlap far from resonance. Thus, the present approach is more sensitive at small detunings and is comparable to Hansch-Couillaud locking at large detunings. For both methods the effective locking width is one free spectral range of the reference cavity.

If cavity 2 of Figure 1 comprises a birefringent cavity, then its reflectances will be given by

$$F_{r1}=F_r(n_c=n_{fast})\ \text{(H polarisation)} \qquad (10)$$
$$F_{r2}=F_r(n_c=n_{slow})\ \text{(V polarisation)}$$

Where the effective cavity refractive indices for the fast and slow axes of the birefringent element are n_{fast} and n_{slow} respectively. Figure 4 shows a comparison of calculated locking error signals for Hansch-Couillaud locking and the method described here, for the case of cavity containing some birefringent element. It is seen that, as with the dichroic cavity case, near resonance the present method produces a steeper error signal, thereby making it more sensitive to small detunings. Again, inset in this figure are the same error signals calculated for several free spectral ranges of the reference cavity, showing that at large detuning, the method of analysing orthogonal modes has a locking signal similar to Hansch-Couillaud locking.

Referring now to Figure 5, there is depicted a specific embodiment of the present invention applied to effect frequency locking of a laser 36. Laser 36 generates a beam 37 which is incident upon cavity 38. Cavity 38 includes a linearly dichroic element 40. Beam 42 is reflected from cavity 38 and received by detector 6. The detector generates a control signal which is applied via cable 34 to laser 36 in order to frequency lock the laser.

Referring now to Figure 6, there is depicted a further embodiment of the present invention. The embodiment of Figure 6 includes a laser 36 which generates a beam 44 that is received by a polarising beam splitter 46. The field associated with beam 44 may be expressed as

$$E_i=E_H\hat{x}_1+E_V\hat{x}_2 \qquad (11)$$

where as before, E_H and E_V and are the complex field amplitudes of the H and V components, however the basis vectors $\hat{x}_1$ and $\hat{x}_2$ are two of the bases of the product space of the spatial and polarisation modes. The basis vector $\hat{x}_1 = HTEM_{00}$ is the component of the field which is both TEM_{00} and H polarised. Similarly, $\hat{x}_1 = VTEM_{01}$ is the component which is both TEM_{01} and V. (The other two products of the vector space $HTEM_{01}$ and $VTEM_{00}$ are zero.) The initial linear polarisation of the laser source determines the fraction of the incident light which goes into each component. Beam splitter 46 produces a vertically polarised beam 60 and a horizontally polarised beam 48. Vertically polarised beam 60 passes, via mirror 52, through a holographic plate 54 that is configured to transform the spatial mode of beam 60 from a TEM_{00} mode to TEM_{01} mode in beam 62. The horizontally polarized beam 48, which is in TEM_{00} spatial mode is combined, via mirror 50, with the TEM_{01} beam by a polarising combiner 56. Combined beam 64 is reflected by empty cavity 58 to generate a reflected beam 66. In the embodiment of Figure 6, cavity 58 is a symmetric, confocal, two-mirror cavity with a Guoy phase-shift given by $\psi=(m+n+1)\pi/2$ where m and n are Hermite-Gauss mode numbers.

It will be realised that other cavities, for example non-confocal cavities and ring cavities might be used in place of confocal cavity 58. Alternatively a whispering gallery mode (WGM) resonator might be used in place of a cavity.

Returning again to Figure 6, cavity 58 is dimensioned so that at a desired locking frequency the $HTEM_{00}$ mode component is resonant with the cavity and so will experience a phase-shift relative to the $VTEM_{01}$ component on reflection. The TEM_{01} spatial mode has two lobes with a relative phase-shift of half a wavelength between them and these are a quarter wavelength shifted in phase from the TEM_{00} component at the locking frequency.

Detector 67 receives the reflected beam 66 and processes it to determine the phase-shift between the horizontal and vertical components of the light and hence the shift between the TEM_{00} and TEM_{01} modes that occurred as a result of the interaction of cavity 58 with beam 64. If the phase-shift is determined to be other than a half wavelength then a suitable error signal is generated and applied via cable 68 for controlling laser 36 back towards locking frequency. It will be noted that one spatial component (TEM_{00}) is H polarised while the other (TEM_{01}) is V polarised. This is so that a polarisation sensitive phase shift detector 67 may be used to detect phase shift between the two spatial modes.

Figure 6A is a block diagram of the internal components of detector 67. Beam 66 is split into two beams 57 and 55 by beam splitter 59. Beam 57 from the splitter is transformed by quarter wave plate 61 and polarising beam splitter 63 to produce a vertically polarised beam. Similarly beam 55 from the beam splitter is transformed by half-wave plate 53 and polarising beam splitter 51 to produce a horizontally polarised beam 49. It should be noted that photodetectors 69 and 71 are split detectors suitable for detecting intensity differences between lobes of beams 65 and 49 respectively. Processor 73 operates on electrical signals from detectors 69 and 71 to produce a control signal on cable 68.

Referring again to Figure 6, the reflectances for cavity 58 are given by:

$$F_{r1}=F_r(m=0,\ n=0)\ \text{(H polarisation)} \qquad (10)$$

$$F_{r2}=F_r(m=0,\ n=1)\ \text{(V polarisation)}$$

Figure 7 is a graph comparing error signals generated by the tilt-locking technique described by D. Shaddock, M. Gray and D. McClelland in *Optics Letters* 24 1499 (1999) with those theoretically capable of being generated by the system of Figure 6. The error signal generated by the embodiment of Figure 6 is theoretically exactly the phase shift ϕ imparted by the cavity. The inset shows detuning over several free spectral ranges of the cavity. In each free spectral range there are two resonances, one from each of the orthogonal modes TEM_{00} and TEM_{01} . It will be observed from Figure 7 that the plot of the error signal that may theoretically be generated by the embodiment of Figure 6 is much steeper near the cavity resonance than that provided by the tilt-locking system and so provides an improved sensitivity to detuning. The improved sensitivity is an advantage in applications using empty wave cavities such as gravity wave interferometry.

Table I lists some examples of the types of cavity that might be used in embodiments according to the present invention along with corresponding orthogonal mode pairs to which the particular cavity would impart a phase difference.

Type of Cavity	Orthogonal Modes	
Empty Cavity	TEM_{00}	TEM_{01} or TEM_{10} etc.
Polarisation dependent (e.g. birefringent, dichroic element)	Horizontally polarised	Vertically polarised
Whispering Gallery Modes (e.g. microsphere)	TE	TM
Physical Obstruction (e.g. transverse wire)	TEM_{01}	TEM_{10}

TABLE 1

Generally, a locking technique according to the present invention may be applied to any case where a cavity, or other resonant means, will partially affect each of two incident components thereby imparting a relative phase shift. The phase shift will be related to the resonance condition of one component. The polarisation assisted phase retrieval technique, embodied without limitation by the sensor of Figure 2, can then be applied to extract the phase shift.

The embodiments of the invention described herein have involved the transformation of radiation from a source into two orthogonal modes, which are orthogonally polarised and incident upon a cavity having a different resonant frequency for each mode. For some cases (e.g. birefringent or dichroic cavities) these requirements are degenerate and the orthogonal polarisations are also the orthogonal modes. In other cases the resonant response is independent of polarisation and a pair of spatial modes are used to obtain a relative phase shift. Thus the present invention encompasses a frequency shift determination technique which depend on the phase shift between two effectively orthogonal modes imparted by a mode selective resonance.

It is important to note that the invention encompasses the use of other phase-shift detectors apart from the polarisation dependent detector that has been explained with reference to Figure 2. Figure 8 shows a radiation source 70 that generates a radiation field that can be generally expressed as:

$$E_i = E_{i1}\hat{x}_1 + E_{i2}\hat{x}_2 \qquad (11)$$

where $\hat{x}_1$ and $\hat{x}_2$ are basis vectors.

The radiation source might be a laser or alternatively it could be radio frequency generator. Radiation field 72 may take the form of a laser beam or it could be a microwave or other radio frequency transmission travelling in a cable or wave guide. Item 74 is a basis discriminating resonant element. That is when radiation field 72 is substantially oscillating at a particular frequency then item 74 will impart a phase shift to the $\hat{x}_1$ component but not to the $\hat{x}_2$ component of field 72. As previously discussed, item 74 could be a dichroic, birefringent or empty cavity for example. Alternatively depending on the nature of the basis vectors $\hat{x}_1$ and $\hat{x}_2$ item 74 may be an antenna or a discrete or distributed electronic circuit. Subsequent to interacting with resonant element 72 the altered field 76 may be represented as:

$$E_a = E_{a1}\hat{x}_1 e^{i\varphi} + E_{a2}\hat{x}_2$$

where $e^{i\varphi}$ is the phase shift. The altered field 76 is received by a detector 78 which recovers φ and makes available a corresponding e_r signal for controlling another device. The device may be the radiation source 70 in which case there is provided a frequency stabilising or locking system.

It will be realised present invention may be readily extended to more exotic dependencies than thus far discussed such as orbital angular momentum, and phase discontinuities or singularities. In these cases the relative phase detection may well involve analysis of properties of the radiation field other than polarisation.

In addition to those applications that have already been discussed the present invention may find application in at least the following: frequency stabilising radio wave devices such as radar transmitters and mobile phones, frequency stabilisation of fibre optic telecommunication systems, frequency stabilisation of semiconductor radiation sources such as diode lasers. Accordingly, the invention encompasses apparatus of the above types incorporating frequency stabilisation techniques as described herein.

It is also envisaged that the invention might be beneficially incorporated into multiple wavelength optical media storage and retrieval devices such as CD-ROM and DVD drives. For example, Figure 8 schematically depicts a DVD drive including

80 including a laser diode arranged to produce a beam 84 to strike an optically encoded disk 88. A portion of beam 84 is diverted by mirror 88 to a processing module 90 which contains an optical cavity and phase shift detector, for example as described with reference to Figure 5 or Figure 6. The processing module 90 generates a control signal which provided to laser diode 82 by conductor 92 in order to facilitate frequency locking. In use the portion of beam 84 that proceeds through mirror 88 is reflected from, and modulated by, rotating disk 84. The modulated beam is then sensed by detector 96 and decoded by processing circuitry in a conventional fashion.

It will be apparent to those skilled in the art that many modifications and/or alterations other than those specifically mentioned can be made without departing from the spirit of the invention, and, as a consequence, the foregoing description of several embodiments is not to be considered in a limiting sense.

Claims:

1. An apparatus for detecting frequency drift of electromagnetic radiation, the apparatus comprising:

phase shifting means arranged to selectively impart differing frequency dependent phase shifts to respective components of the electromagnetic radiation; and

phase detection means responsive to the phase shifting means and arranged to generate a control signal dependent on the phase shifts.

2. An apparatus according to claim 1, including a means to generate the electromagnetic radiation.

3. An apparatus according to claim 2, wherein the means for generating the electromagnetic radiation is responsive to the control signal and so is frequency locked.

4. An apparatus according to claim 2, wherein the phase shifting means is responsive to the control signal.

5. An apparatus according to claim 4, wherein the phase shifting means comprises a resonant cavity, the active length of which alters in response to the control signal.

6. An apparatus according to claim 1, wherein the phase detection means is be arranged to detect a relative phase shift between orthogonal components of the electromagnetic radiation.

7. An apparatus according to claim 6, wherein the phase detection means is arranged to detect a relative phase shift between horizontally and vertically, polarised components of the electromagnetic radiation.

8. An apparatus according to claim 1, wherein the phase detection means is arranged to a detect a relative phase shift between orthogonal spatial mode components of the electromagnetic radiation.

9. An apparatus according to claim 2, wherein the means to generate the electromagnetic radiation is an RF oscillator

10. An apparatus according to claim 2, wherein the means to generate the electromagnetic radiation is an optical frequency source of electromagnetic radiation.

11. An apparatus according to claim 9, wherein the RF oscillator comprises a microwave frequency oscillator.

12. An apparatus according to claim 10, wherein the optical frequency source comprises a laser.

13. An apparatus according to claim 1 wherein the phase shifting means comprises any one of: an antenna, a microwave reflector, a resonant cavity.

14. An apparatus according to claim 10, wherein the phase detection means includes optical elements arranged to analyse the polarisation state of the electromagnetic radiation.

15. An apparatus according to claim 1, wherein the phase detection means further includes a number of transducing means arranged to transduce components of the electromagnetic radiation into corresponding electrical signals.

16. An apparatus according to claim 15, wherein the phase detection means includes electronic processing circuitry arranged to produce the control signal.

17. An apparatus according to claim 16, wherein the phase detection means includes digital electronics including a digital processor arranged to process signals from the transducing means in order to produce the control signal.

18. An apparatus according to claim 1, wherein the phase detection means is arranged to produce a control signal that is the relative phase shift imparted by the cavity.

19. An apparatus according to claim 1, wherein the phase detection means is arranged to produce a control signal that is the tangent of the relative phase shift imparted by the cavity.

20. A laser locking assembly including:

a resonant cavity configured to impart differing frequency dependent phase shifts to respective components of a laser beam and to exhibit resonance for a particular component at a desired locking frequency;

a phase detector responsive to the resonant cavity and arranged to generate a control signal dependent upon relative phase shift between said components imparted by the cavity; and

a laser for generating the laser beam and responsive to the control signal for frequency stabilisation at the locking frequency.

30. An assembly according to claim 20, wherein the resonant cavity is anisotropic and is configured to impart the frequency dependent phase shift to orthogonal linearly polarised components of the laser beam.

31. An assembly according to claim 30, wherein the phase detector is arranged to produce the control signal on the basis of the polarisation state of light from the resonant cavity.

32. An assembly according to claim 32, wherein the phase detector is a Stokes parameter detector.

33. An assembly according to claim 32, wherein the phase detector includes transducing means arranged to detect intensities of diagonal and right-circular polarised components of light respectively.

34. An assembly according to claim 33, wherein the transducing means includes photodetectors and wave plates.

35. An assembly according to claim 33, wherein the transducing means includes a means to convert a portion of the laser beam into a spatial mode component that is orthogonal to the remainder of the beam. In that case the cavity may be empty and configured to selectively impart a frequency dependent phase shift to a particular one of said spatial mode components.

36. An optical disk drive including a laser locking assembly according to claim 1.

37. An optical disk drive including a laser locking assembly according to claim 20.

38. A method for detecting frequency drift of electromagnetic radiation including the steps of:

imparting differing phase shifts to respective components of the electromagnetic radiation depending on deviation of the frequency of the electromagnetic radiation from a centre frequency;

subsequently detecting a relative phase shift between said components; and

generating a control signal depending on the imparted relative phase shift detected.

39. A method according to claim 38 wherein the step of imparting the phase shifts includes causing the electromagnetic radiation to interact with a resonant element of a type that exhibits a resonance for one component of said radiation at the centre frequency.

40. A method according to claim 38 including a step of generating the electromagnetic radiation.

41. A method according to claim 40 including a step of generating the electromagnetic radiation in response to the control signal thereby frequency locking the electromagnetic radiation.

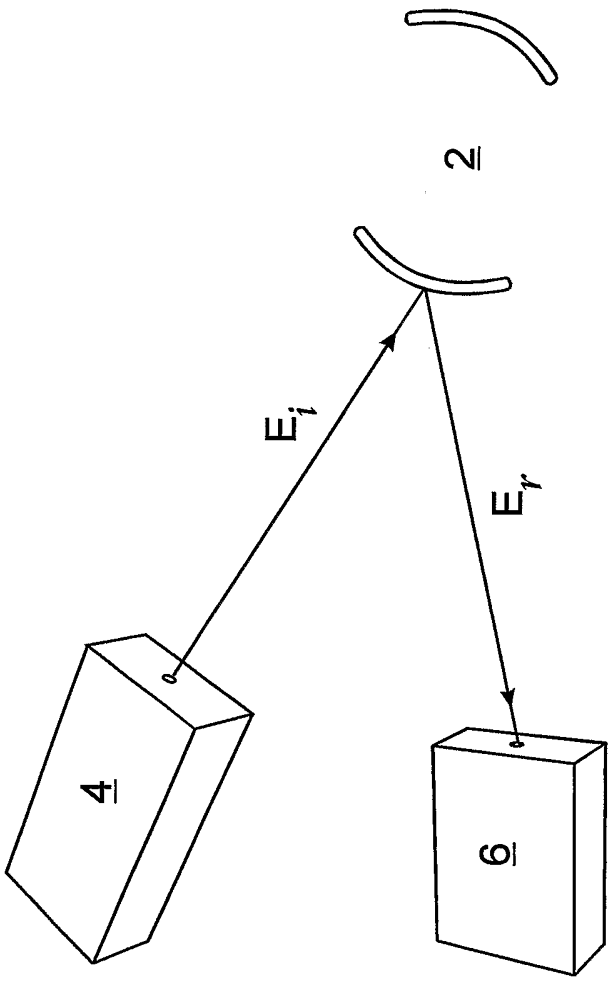


FIG. 1

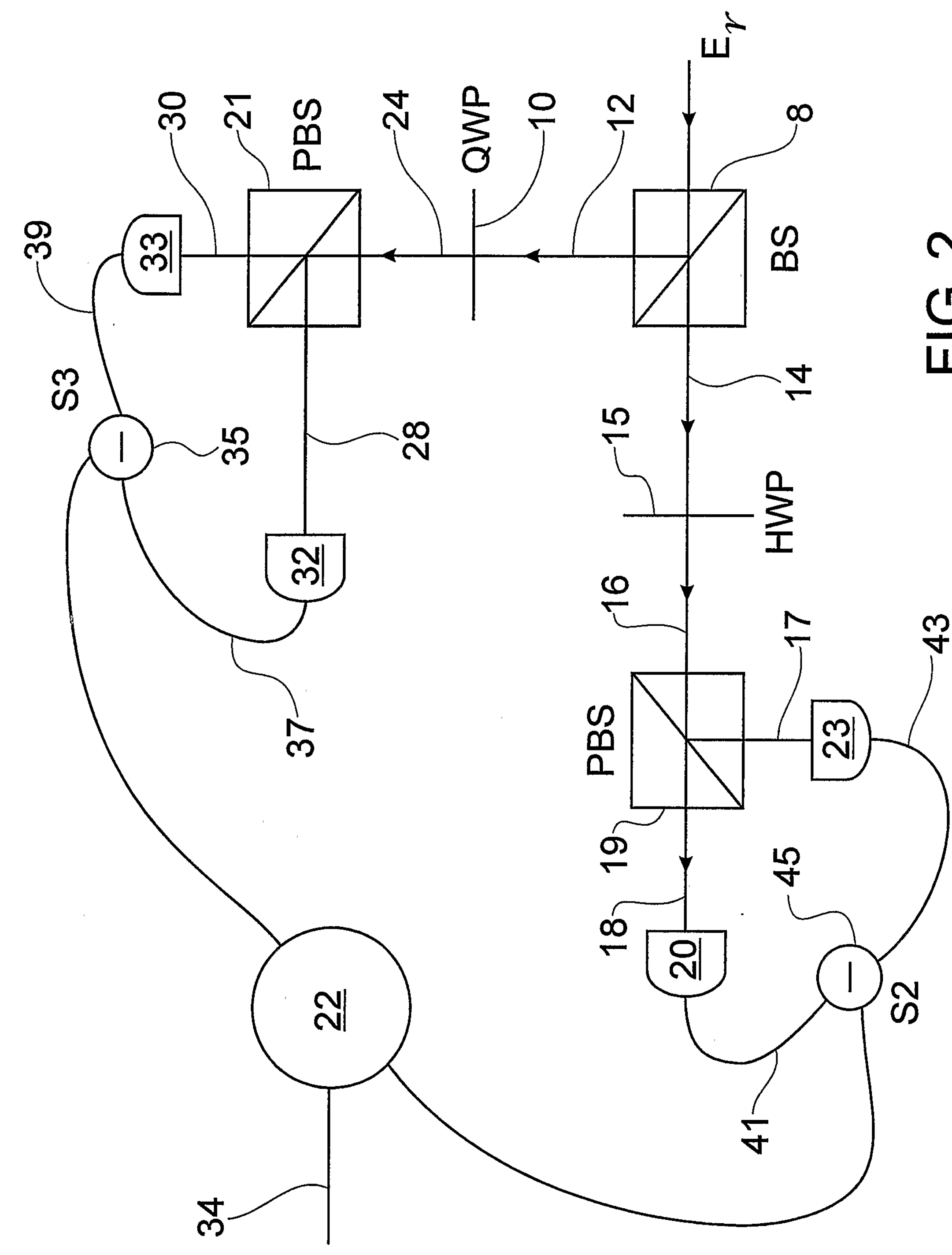
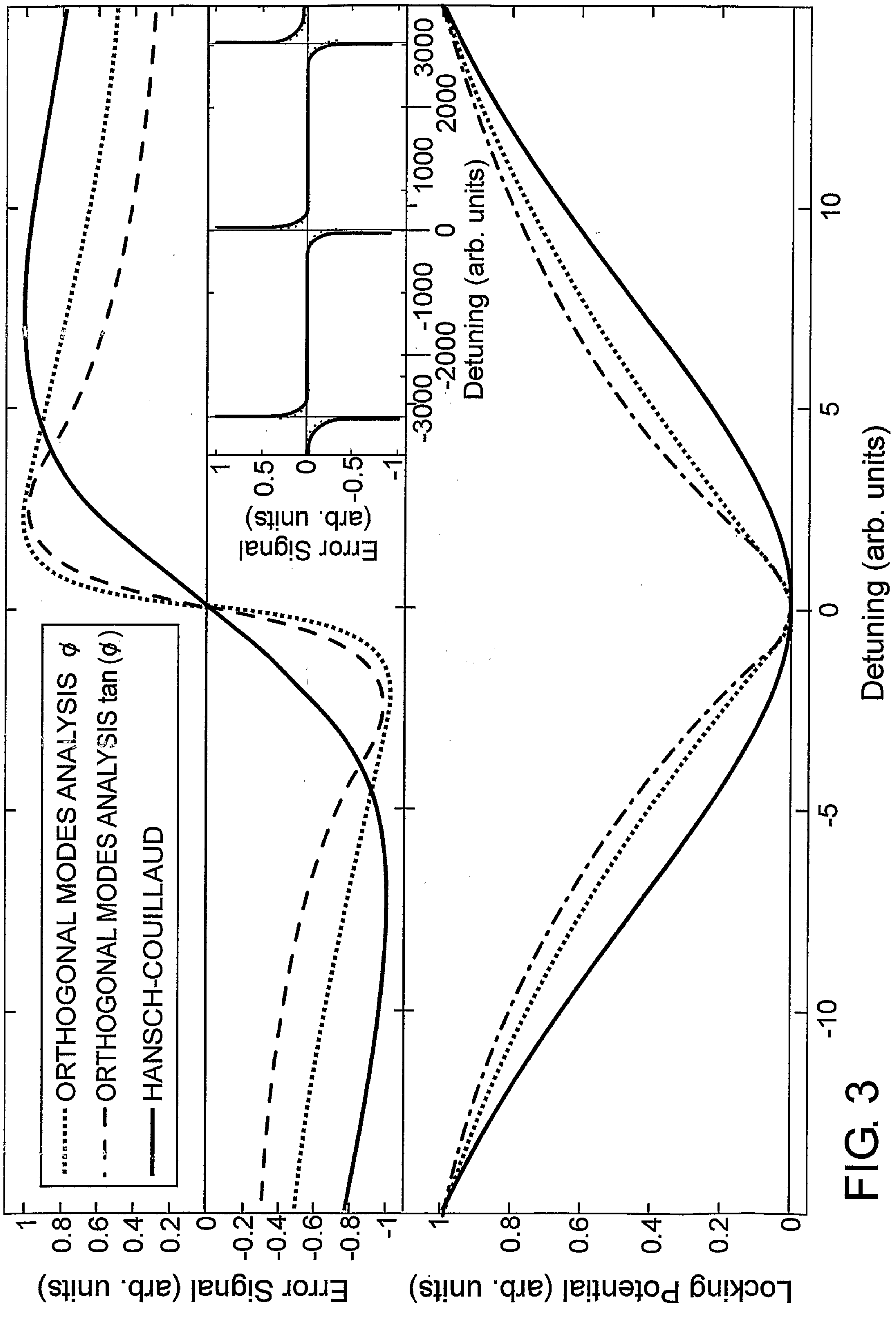

E γ
8
BS
12
10
QWP
24
PBS
21
30
33
39
S3
35
28
32
37
14
15
HWP
16
17
PBS
23
43
19
45
18
20
S2
41
22
34

FIG. 2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ORTHOGONAL MODES ANALYSIS tan (ϕ)
HANSCH-COUILLAUD
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Locking Potential (arb. units)
Detuning (arb. units)
Error Signal (arb. units)
Detuning (arb. units)

FIG. 3

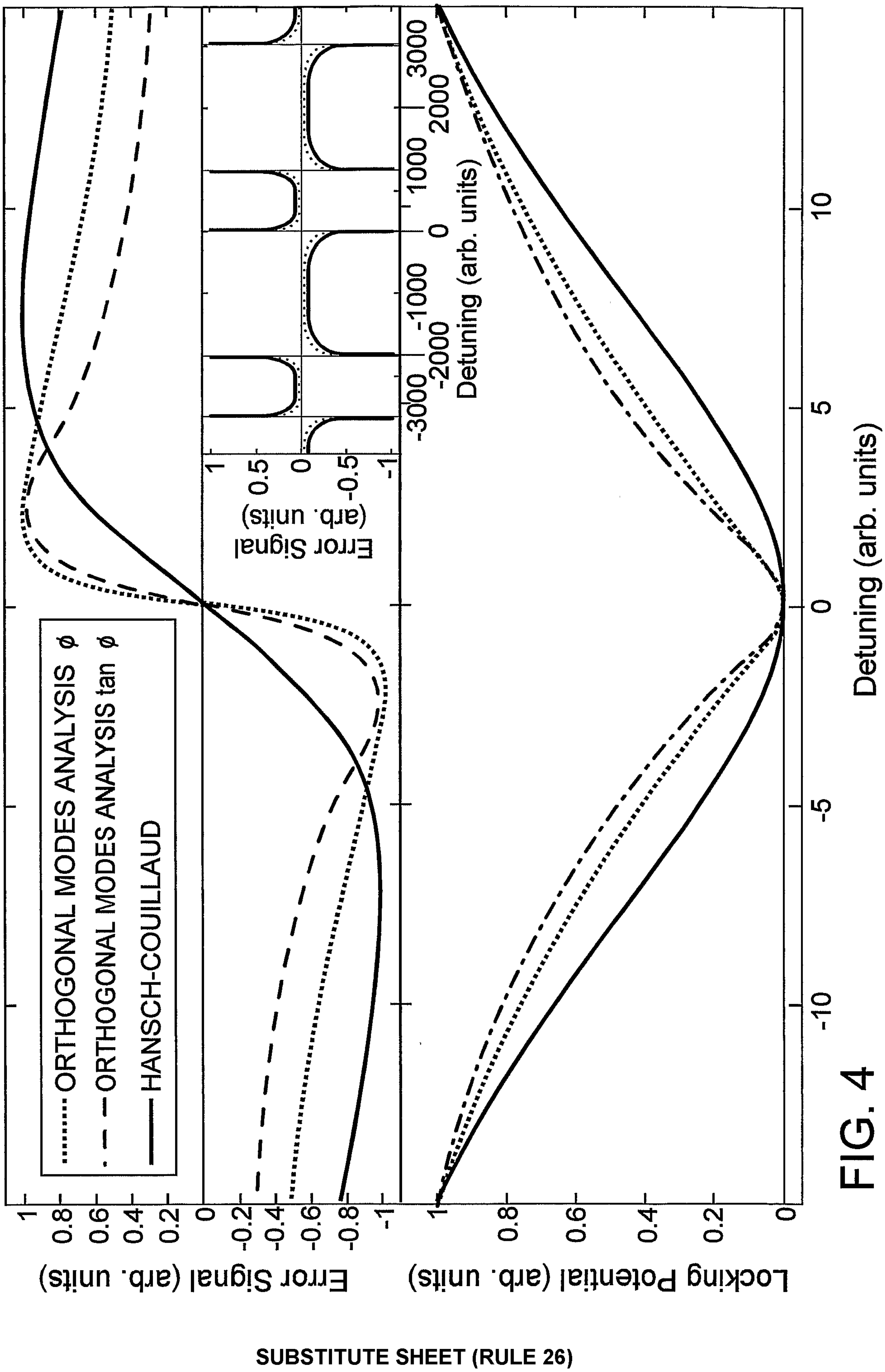
ORTHOGONAL MODES ANALYSIS φ
ORTHOGONAL MODES ANALYSIS tan φ
HANSCH-COUILLAUD
Error Signal (arb. units)
Error Signal (arb. units)
Detuning (arb. units)
Locking Potential (arb. units)
Detuning (arb. units)

FIG. 4

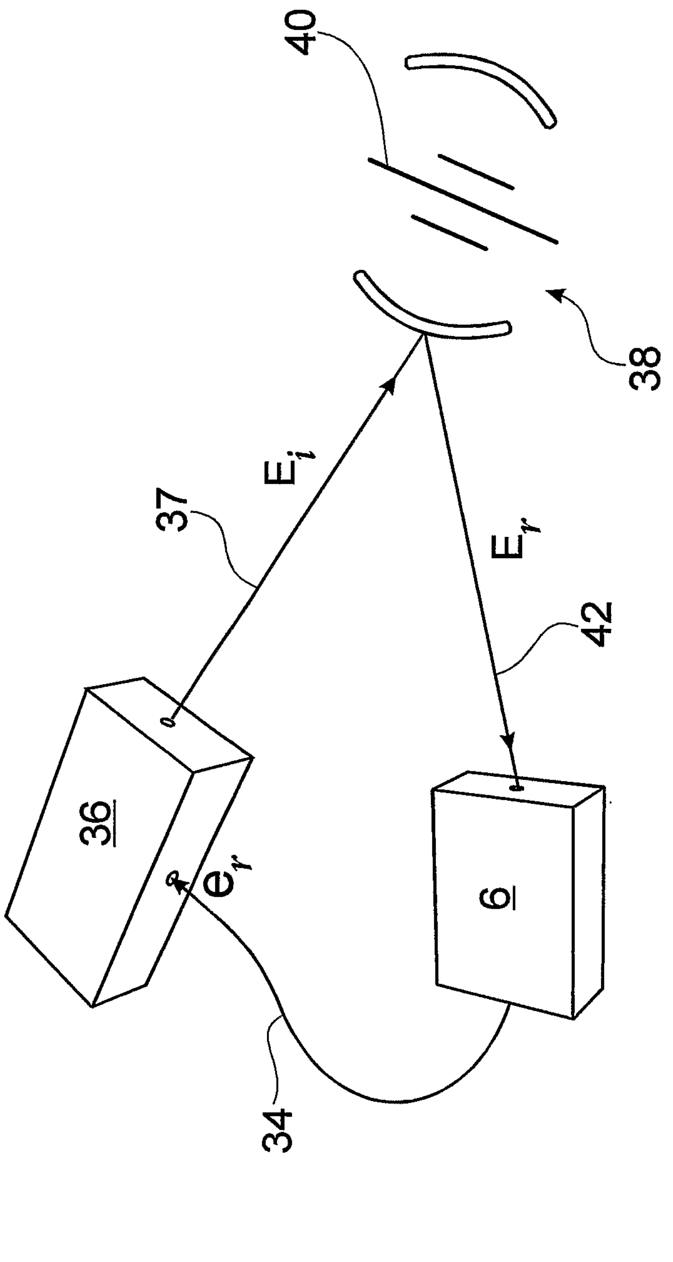

FIG. 5

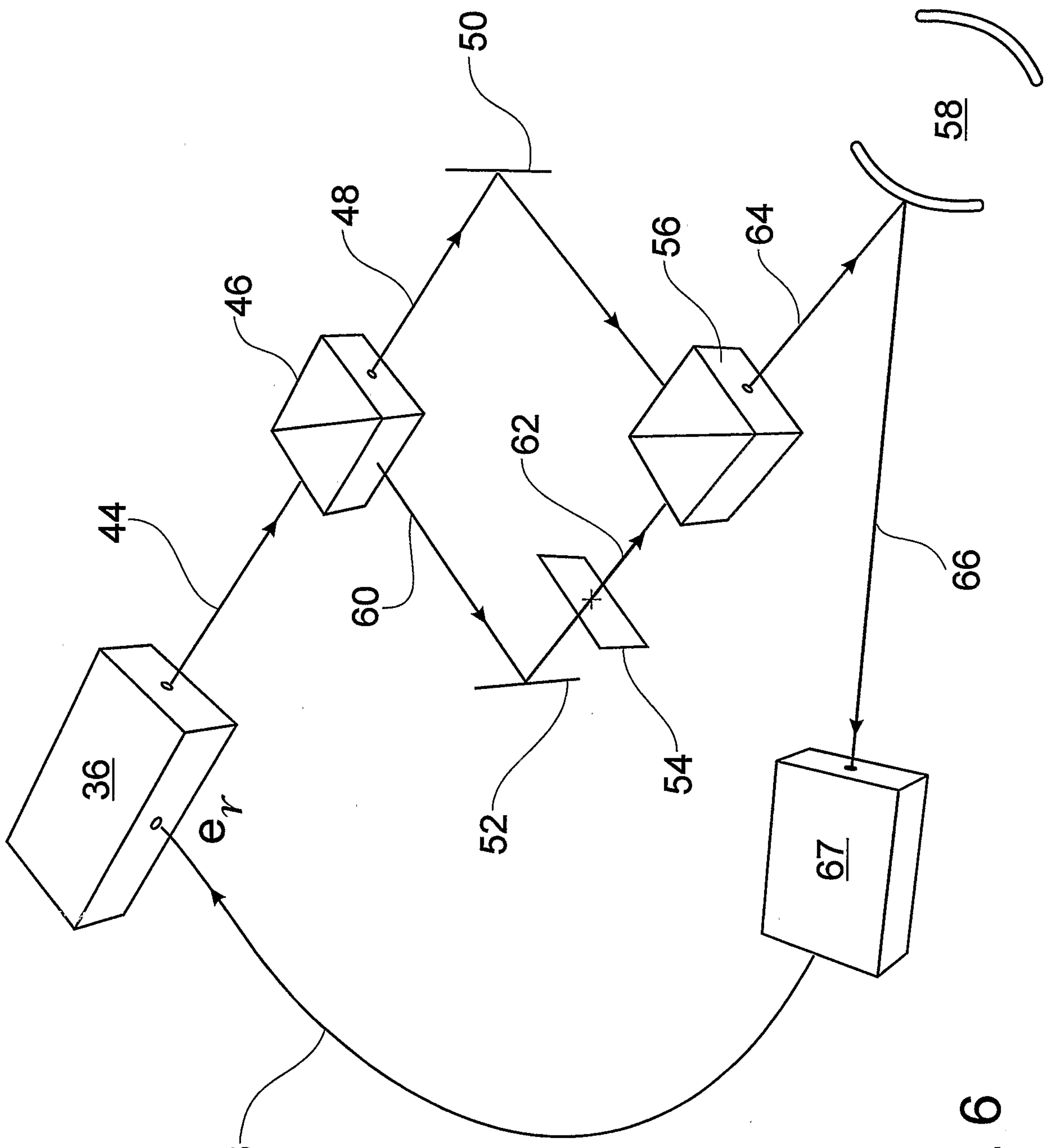

FIG. 6

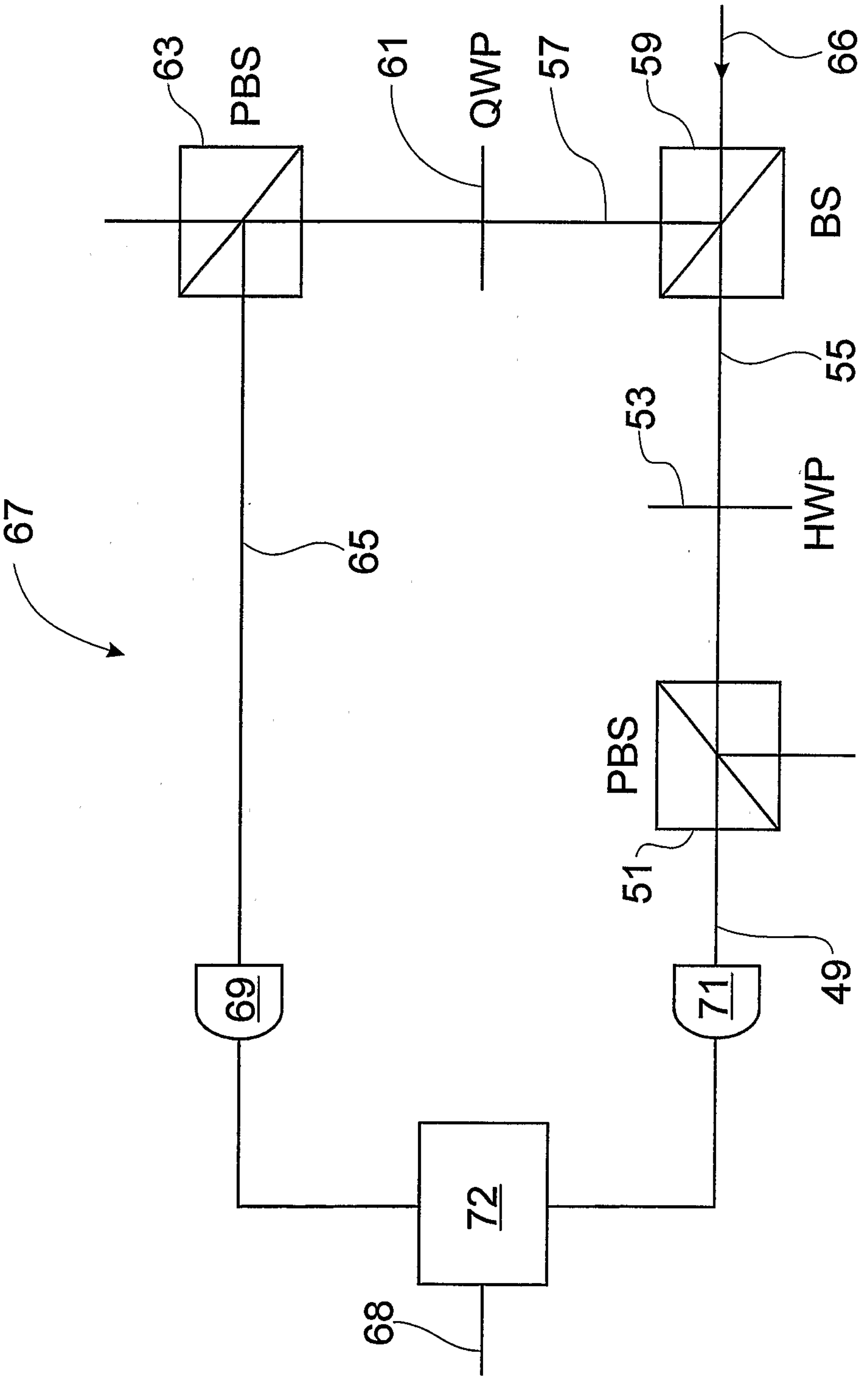

FIG. 6A

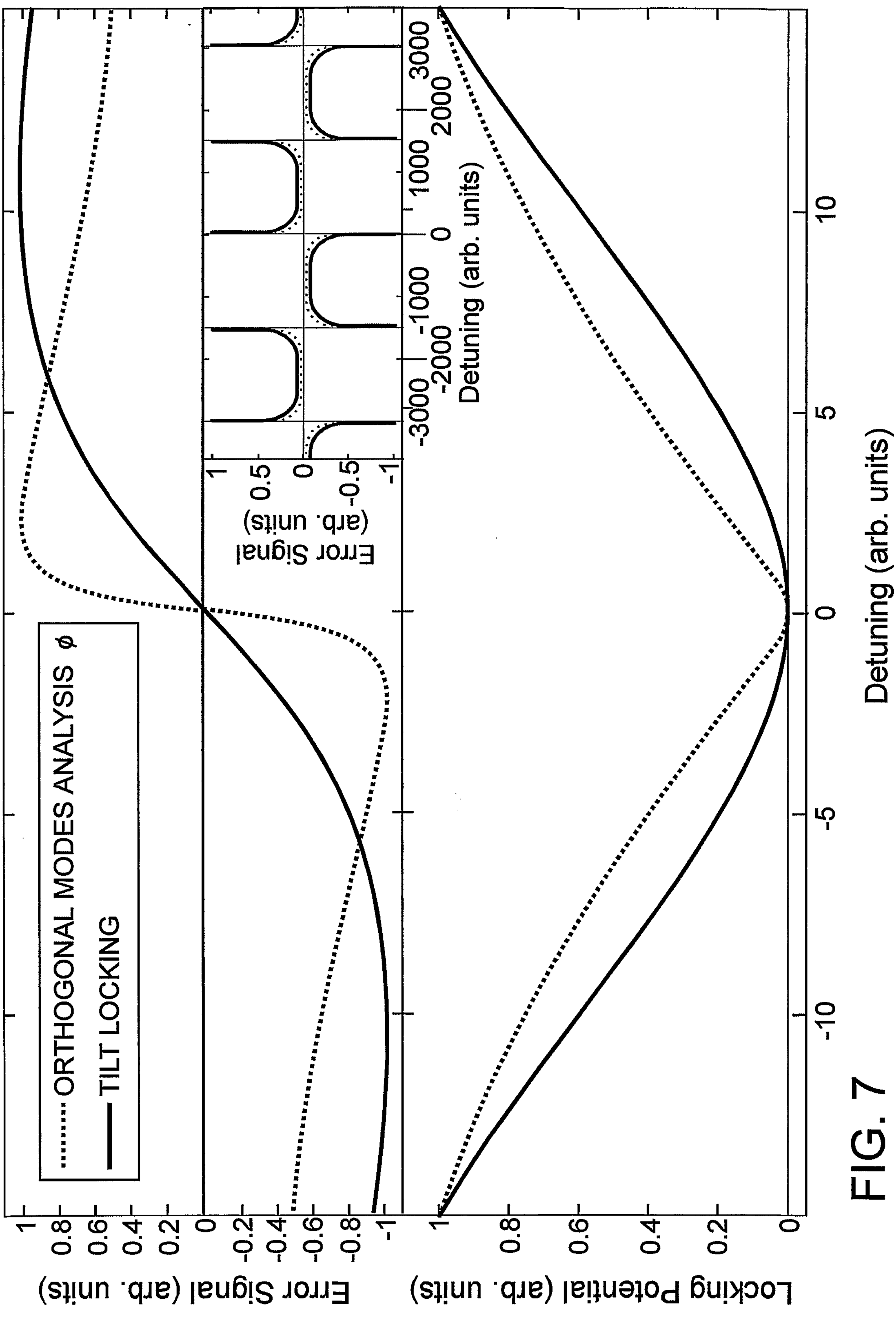
ORTHOGONAL MODES ANALYSIS φ
TILT LOCKING
Error Signal (arb. units)
Locking Potential (arb. units)
Detuning (arb. units)
Error Signal (arb. units)
Detuning (arb. units)
-3000
-2000
-1000
0
1000
2000
3000
1
0.5
0
-0.5
-1
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
1
0.8
0.6
0.4
0.2
0
-10
-5
0
5
10

FIG. 7

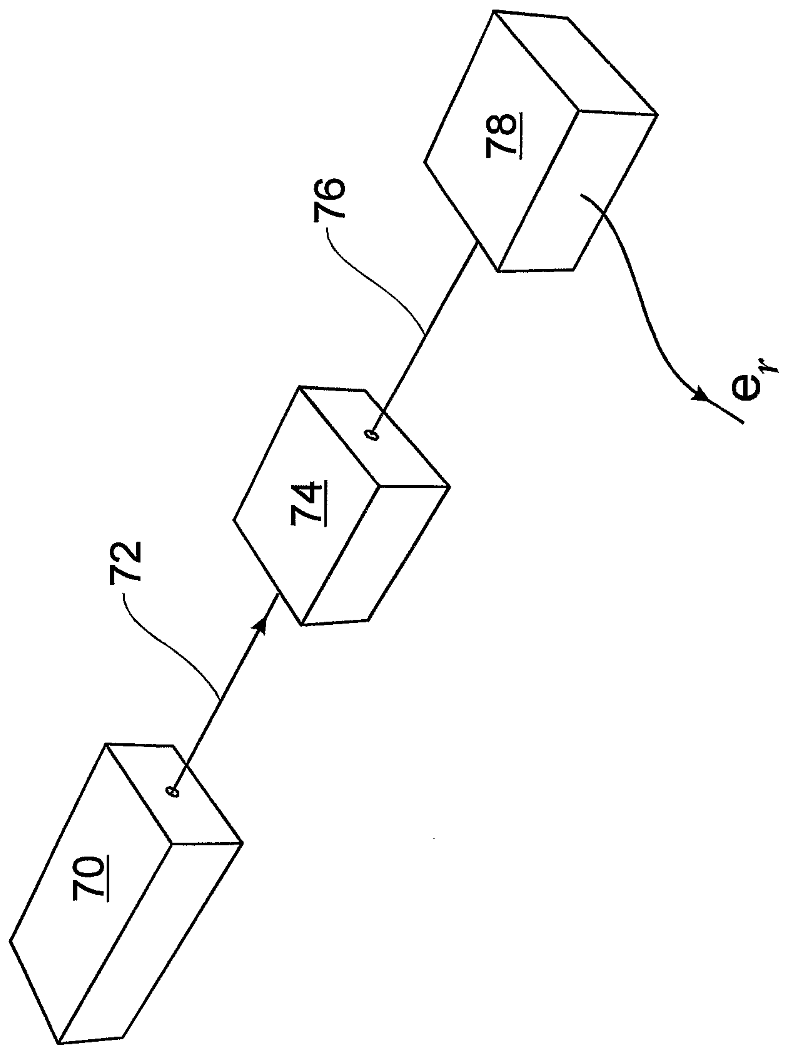

FIG. 8

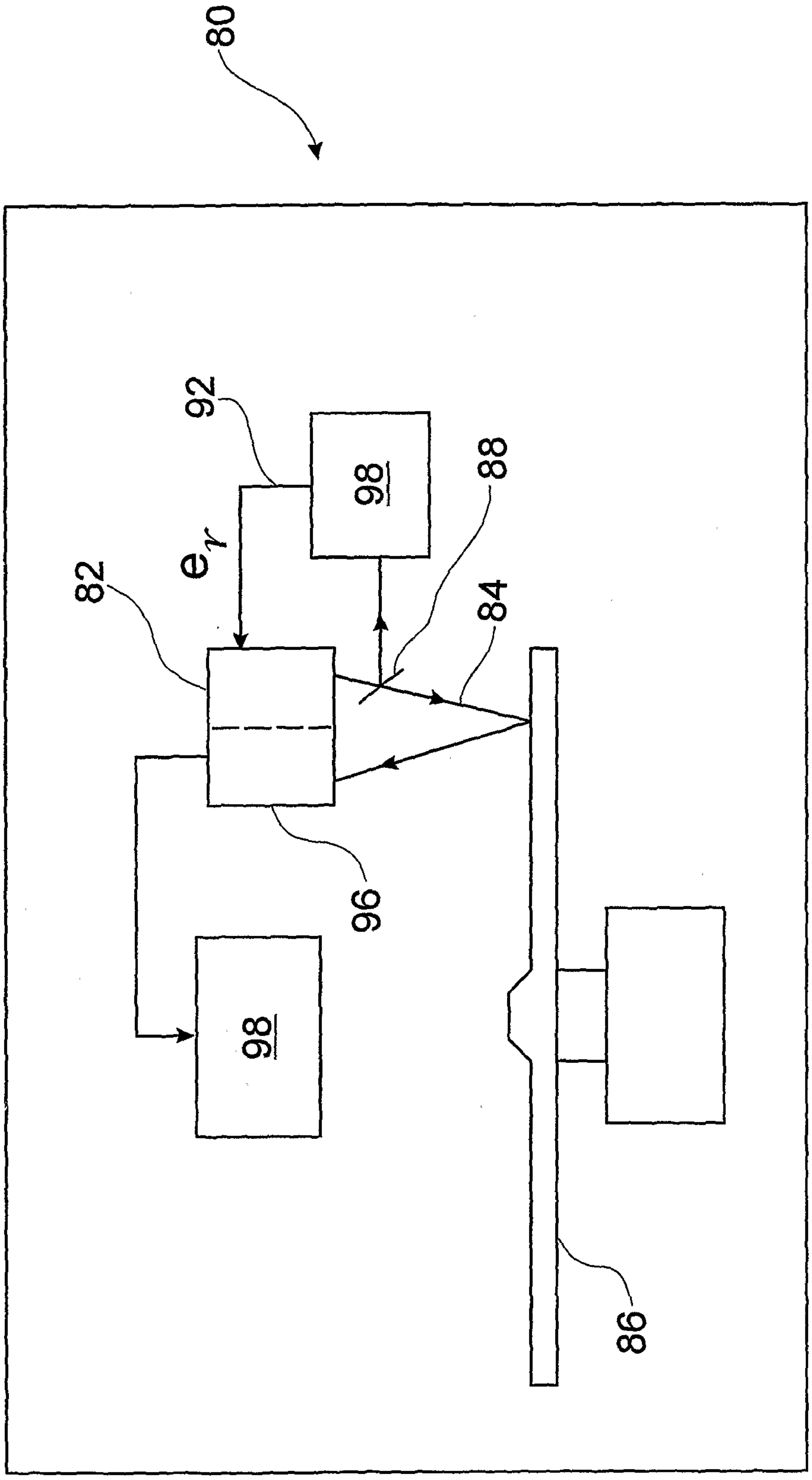

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2004/000591

A. CLASSIFICATION OF SUBJECT MATTER	
Int. Cl. 7: H01S 3/098	
According to International Patent Classification (IPC) or to both national classification and IPC	
B. FIELDS SEARCHED	
Minimum documentation searched (classification system followed by classification symbols)	
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched	
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) WPAT. KEYWORDS: FREQUENCY, PHASE, DRIFT, SHIFT, STOKES AND SIMILAR	

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X, P	HARVEY, MICHAEL D et al, "FREQUENCY LOCKING BY ANALYSIS OF ORTHOGONAL MODES", OPTICS COMMUNICATIONS 221 (2003) 163-171, ELSEVIER.	1-41
A	SHADDOCK, D A et al, "FREQUENCY LOCKING A LASER TO AN OPTICAL CAVITY USING SPATIAL MODE INTERFENCE", OPT. LETT. 24, 1499 (1999).	
A	US 6198757 B1 (BROUTIN et al) 6 MARCH 2001	
A	MUELLER, GUIDO et al, "DETERMINATION AND OPTIMIZATION OF MODE MATCHING INTO OPTICAL CAVITIES BY HETERODYNE DETECTION", OPTICS LETTERS, VOL. 25, NO. 4, 15 FEBRUARY 2000.	

☐ Further documents are listed in the continuation of Box C   ☒ See patent family annex

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 16 September 2004	Date of mailing of the international search report 28 SEP 2004
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. (02) 6285 3929	Authorized officer **RICHARD REED** Telephone No : (02) 6283 7927

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/AU2004/000591

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member
US	6198757	

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX