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(54) DEVICE FOR PROCESSING OPTICAL SIGNALS

(71) We, WESTERN ELECTRIC COMPANY, INCORPORATED, of 222 Broadway, New York City, New York State, United States of America, a Corporation organized and existing under the laws of the State of New York, United States of America, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which is is to be performed, to be particularly described in and by the following statement:-

This invention relates to devices for processing optical signals.

The development of the laser has influenced many areas of technology and in some has provided for devices far beyond the ken of the original pioneers in this field. So, for example, the laser has established a significant role in fields as diverse as medicine, civil engineering, semiconductor device fabrication, various manufacturing processes and of course general research and development. One major application, predicted by early workers in the field of laser technology, is still in a period of dynamic growth. This application involves the use of lasers in the field of communication. Although the obvious advantages of such an application in terms of greater bandwidth are widely recognized, problems of transmission and signal processing are formidable. In the field of transmission the development of optical fibers appears to have been a significant step along the road to effective transmission of optical signals. In the area of signal processing, some direct processing of optical signals through the use of nonlinear materials has been realized, and solid-state lasers will, in all probability, be useful as miniature light sources in future communications systems. However, the ultimate step to completely integrated optical circuitry has yet to be fully realized. Such integrated optics, comparable in scale and function to integrated electronic circuitry, would enable the engineer to work with optical signals in much the same way as one works with electrical signals today. Transformation of the optical signal to an electronic signal would occur only at the extreme terminals of the communication system, if at all. All amplifying and switching operations would occur with the signal in its optical form without intermediate electronic devices. The realization of completely integrated optical circuitry has been delayed for lack of a viable optical amplifier -- a device akin to a transistor but which would not require any intermediate electronic devices. This application discloses such an optical amplifier.

Specific characteristics of nonlinear absorbers have long been known. Generally, light impinging on a linear absorptive medium will diminish in strength as it passes through the medium according to the formula

$$I_L = I_O e^{-\beta L} \qquad (1)$$

Here I_O is the initial beam intensity, I_L is the intensity at any distance L in the medium and β is the absorption coefficient embodying the absorption characteristics of the medium. β is a known function of the impinging beam wavelength, for a given medium, and displays larges increases in the region of ground state transitions. So, for example, in the case of a gas the absorption is very strong at a wavelength that connects one of the ground states with an excited state.

Despite the strong absorption of the impinging beam in the region of a transition, it has been found that as the beam intensity is increased a region is found where the absorbed energy approaches a maximum. This occurs when the intensity of the beam is sufficiently high to "excite" approximately half of the atoms to the upper state. At equilibrium this is the largest number of atom allowed in the upper state at any given time. Under these circumstances any additional light impinging on the gas will not be absorbed. The medium is then said to be bleached or saturated. It has been previously shown that the transmission characteristics of a resonant optical cavity may be significantly altered when filled with such a saturable absorber. A simple heuristic argument will serve to demonstrate this fact.

An empty resonant optical cavity consists of two plane mirrors of high reflectivity placed at a distance L from one another. When light of intensity I_O impinges perpendicularly on one mirror an amount I_OT is transmitted into the cavity. Here T is the transmission of the appropriate mirror and is generally less than one. Once inside the cavity the light is reflected back and forth between the mirrors, some light being transmitted through the mirrors on each pass. If the distance between the mirrors is a multiple of one-half of the optical wavelength, then the cavity is said to be in resonance with the light, which light is then transmitted with little loss. This transmission is due to constructive interference of the light associated with each of the passes at the mirror surfaces. When this condition obtains, the intensity within the cavity is approximately

$$I_C=\frac{I_T}{T} \qquad (2)$$

Here I_C is the intracavity intensity and I_T is the transmitted intensity. Since at resonance

$$I_T \simeq I_O \qquad (3)$$

we obtain

$$I_C= I_O/T> I_O. \qquad (4)$$

The light intensity within the cavity is greater than that incident on the cavity because of the multiple intracavity reflections.

Now consider the cavity to be filled with a saturable absorber which saturates when irradiated with light of intensity I_S. When light of intensity I_O impinges at right angles to one of the plates of the cavity the intensity transmitted into the cavity,

$$I_{TC} = I_OT, \qquad (5)$$

$$I_C = I_S = I_O/T$$

decays exponentially with distance according to equation 1. As a result of this decay very little energy reaches the second mirror and efficient multiple reflections do not occur. If, however, the power transmitted into the cavity, I_{TC}, is equal to I_S

$$I_{TC} = I_S \qquad (6)$$

then the power entering the cavity is sufficiently high to saturate the absorber and any additional light will pass through the medium as though it were not there. Under these conditions, the cavity is said to be switched on. It is then clear from equations 5 and 6 that the incident intensity which will turn the cavity on is given by

$$I_{O\ \mathrm{TURN\ ON}} = I_S/T \qquad (7)$$

Now consider that the cavity is turned on and that the incident intensity is lowered. We want to observe the intensity at which the cavity turns off. It is obvious from our prior discussion that the medium will cease to be transmitting when the internal cavity intensity goes below I_S. The internal cavity intensity, however, is given by equation 4

$$I_C = I_O/T \quad .$$

The turn-off condition then becomes

$$I_C = I_S = I_O/T \qquad (8)$$

$$I_{O\ TURN\ OFF} = I_S T \quad . \qquad (9)$$

When the impinging intensity becomes less than $I_S T$ the cavity will turn off. While the above argument is only qualitative, comparing equation 7 with equation 9 demonstrates that, since T is less than 1, the incident intensity at which the cavity turns on is greater than the intensity at which the cavity turns off. Consequently, while the power within the cavity may be related in a single valued way to the transmitted power, the relationship between the input power and the cavity power, and hence that the input and output power is dual valued.

This bistability was first disclosed by H. Seidel in U.S. patent 3,610,731 and was applied by A. Szoke in U.S. patent 3,813,605 to the product of short optical pulses with variable lengths. Szoke also describes in his disclosure applications similar to square wave amplification, inversion, and triggering. However, there is no indication in the prior art that this device can be operated in other than an absorptive bistable mode. We have previously discovered that under certain operating conditions a primarily dispersive bistable device is realized. Since out bistable device is primarily dispersive it displays significantly less loss than the absorbtive bistable device. We have also determined that under certain operating conditions the region of bistability degenerates into a single valued relationship with differential gain so that a device for amplifying light signals is realised.

This device is described in more detail in U.S. patent specification No. 4,012,699. An example which is particularly described in that patent specification involves the use of sodium vapour as the non-linear medium in a Fabry Pérot cavity. Under suitable operating conditions, a bistable characteristics or a characteristic exhibiting differential gain can be obtained in which the dispersive properties of the medium dominate or at least contribute equally with the absorbtive properties.

According to the present invention there is provided a device for processing optical signals comprising an optical cavity formed by at least two surfaces which reflect light of the wavelength of the optical signals, a non-linear medium within the optical cavity and means for introducing the optical signals into and extracting them from the cavity, the cavity and medium being such as to provide an output intensity/input intensity characteristic having a region exhibiting bistability or differential gain without population inversions being produced in the medium, in which region the dispersive properties of the medium dominate or are equal to the absorbtive properties and the non-linear dispersive properties of the medium include contributions due to non-driven states which are greater than ten percent of the contributions if any due to driven states.

Properties of the medium and the cavity may be varied to provide bistable or single-valued-amplifying modes of operation. Properties which may be so varied include the density of the medium, it length, its temperature, impurity levels of the medium, the separation of the mirrors and their relative orientation, the orientation, polarisation, intensity and frequency of the light entering the cavity, as well as the introduction of more than one beam of light into the cavity. While the operating wavelength may be anywhere in the electromagnetic spectrum depending on the medium, the invention will most likely be practised in the optical region by which is meant the ultraviolet (500 Angstroms-4500 Angstroms) infrared (7500 Angstroms-25μ) or visible (4500 Angstroms-7500 Angstroms).

The most practical embodiment of this invention will involve a solid nonlinear materia, with cleaved ends to form reflecting surfaces and advantageously coated to increase reflectivity. Preferred materials are those with $|n_2| > 10^{-13}$ cm$_2$/statvolt$_2$ where n_2 is the coefficient of the term in the field-dependent refractive index which is quadratic in field.

Once one has at one's disposal an optical amplifier of the type described above, one may perform many functions in direct analogy with the more familiar electronic amplifiers. These include but are not limited to simple a.c. amplification, clipping, limiting, discrimination and positive and negative feedback.

Some embodiments of the invention will now be described by way of example with reference to the accompanying drawings, in which:-

Figure 1 is a schematic representation of the driven and nondriven states.

Figure 2 is a schematic representation of a device according to the invention using ruby as the non-linear medium.

Figure 3 is a schematic representation of a ruby laser for use in conjunction with the device of Figure 2.

We have discovered that generally non-linear dispersive effects which results in amplification or bistability may be associated with two distinct groups of quantum states. To illustrate these groupings consider a case where two or more states are driven by resonant or near resonant irradiating light, while the total dispersive effect due to the medium dominates the absorbtive effect. The driven states (by which we mean those states whose population is directly altered by resonant absorption or resultant relaxation phenomena as illustrated in Figure 1) make both absorptive and dispersive contributions to the overall interaction between the medium and the radiation. However, we have shown that additional dispersive contributions -- even greater than 10 percent of the dispersive contribution due to the driven states -- may be made by nondriven states. Consequently, absorbtive phenomena which effect the population of the driven states yield not only the dispersive effects associated with the driven states but also yield significant dispersive effects associated with the nondriven states. In the case of sodium (the medium particularly described in our U.S. patent specification No. 4,012,699) the dispersive effects due to the nondriven states are small and certainly less than 10 percent of the dispersive effects due to the driven states. In the following examples, however, the dispersive effects associated with the nondriven states are significant and greater than 10 percent of the dispersive effect associated with the driven states.

EXAMPLES

1. *Ruby*

In the operational modes of interest in the following examples the dispersive characteristics of the medium -- due to both the driven and nondriven states -- dominate the absorptive characteristics of the medium. The relative contributions of the various dispersive and absorptive effects may take on different values, some of which are quite unexpected. For example, the absorptive contribution associated with the driven states may dominate the dispersive effects associated with the driven states, yet the dispersive contributions due to the nondriven states will result in the domination of the absorptive effect by the *total* dispersive effect. In all of the following examples the dispersive contributions of the nondriven states is at least 10 percent of the dispersive contributions of the driven states. Clearly, nondriven contributions of 50 percent or greater than 100 percent of the driven state contribution may even be more desirable. In each of these cases, the population of driven states introduces increased dispersive contributions due to the nondriven states. This allows for a situation in which the absorption associated with the driven states and hence the dispersion associated with the driven states is small. Yet, the total dispersive effect is large due to the contributions of nondriven states. The low absorption allows for low input power yet the large total dispersion yields effective bistable and amplifying characteristics.

In review, the nonlinear dispersive properties of the medium are made to dominate its nonlinear absorptive properties by inducing real transitions within the material through the absorption of light. The nonlinear dispersion associated with the driven states is enhanced by contributions from nondriven states. The resultant nonlinear dispersion associated with the medium dominates the absorptive effect and may combine with the cavity characteristics to yield the bistable and amplifying properties alluded to above. The absorption, while in and of itself contributing only minimally to the amplifying and bistable phenomena, causes a transition which results in large nonlinear dispersion. The resultant device displays either bistable or amplifying characteristics primarily because of the combination of the optical properties of the cavity and the dispersive, rather than the absorptive, properties of the medium. As in analogous electronic devices the gain characteristics of the amplifying device allows for operation, at times using more than one such device, in numerous modes; for example, a.c. amplification, clipping, limiting, descriminating, positive and negative feedback, oscillation, frequency multiplexing and demultiplexing and numerous logic modes.

In this example, ruby was used as the nonlinear medium. Cr^{3+} ions may be elevated to the $2\bar{A}$ and $\bar{E}$ excited states by absorbing light of approximately 6934 Angstroms. If this system is considered as a simple two-state system, with the effects of other nondriven states consequently being neglected, then the nonlinear dispersion associated with the driven states is found to be very small at room temperature. Consequently, one would expect that the ruby device must be operated at very low temperatures in order to permit near resonant operation with a concommitant increase in the nonlinear dispersion associated with the driven states. However, applicants have found that the significant contribution of the nondriven states in this system to the nonlinear dispersion allows for room temperature operation of the ruby device in the dispersive mode. It should be noted that in nonlinear media generally the dispersive properties of the system are dependent on the population of the various states. The absorption of light changes the population of these various states thereby resulting in an intensity dependent or nonlinear dispersion. However, in this example and in the following example, the nonlinear dispersion is additionally affected in a very significant way be contributions from nondriven states.

A schematic representation of the ruby device is shown in Figure 2. In this Figure, 91 is a quartz element with an associated spherical mirror surface 92 having approximately 90 percent reflectivity at 6934 Angstroms. 93 is a ruby element 1/2 cm thick and 1/4 inch in diameter with a 91.5 percent reflecting surface 95 and a transmitting surface 94 with an antireflective coating. The radius of curvature of the spherical surface 92 is 0.87 cm. Light of approximately 6934 Angstroms wavelength represented by 96 is introduced into the cavity. The laser source 97 includes an isolator. The light has a power density of greater than 100 watts/cm^2 and has a beam waist of 40 microns as it impinges on the ruby. The device has been operated in all modes with maximum input powers of between 150-600 watts/cm^2. The bistable and amplifying operation was obtained as shown in the Table. The transition from bistable to amplifying operation may be obtained in exemplary embodiments by varying the cavity temperature, the optical path length of the cavity, the concentration of chromium in the ruby, the crystal thickness, or the laser frequency or polarizarion or combinations thereof. A 5-20 msec. switching time was observed consistent with the 3-5 msec. excited state lifetime of the chromium ion in the ruby.

In the room temperature ruby device irradiated at 6934 Angstroms the dispersive contribution due to nondriven states exceeds the dispersive contribution due to the driven states. In fact if the irradiating light is adjusted so as to connect the ground state to a point between the $2\bar{A}$ and $\bar{E}$ excited states the dispersive contributions from these two driven states, being of different sign, will cancel. In such an event the only dispersive contribution is due to the nondriven states.

TABLE

Length mm	Crystal Conc. %Cr3+	Temp. K	Low Intensity Laser-Cavity Mismatch Angle (radians)	Mode	Ruby Laser Temp. K
5	.05	296	0	limiter	77
			.08	AC gain	
			.11	AC gain	
			.14	bistable	
			.18	bistable	
			.20	bistable	
5	.05	120	0	bistable	77
			.04	bistable	
			.07	bistable	
			.11	AC gain	
			.14	AC gain	
			.18	AC gain	
5	.03	105	0	limiter	77
			.12	bistable	
			.16	bistable	
			.20	bistable	
3	.03	95	0	limiter	65
			.08	AC gain	
			.12	bistable	
			.16	bistable	
			.20	bistable	
3	.03	95	0	bistable	77
			.04	bistable	
			.08	bistable	
			.12	bistable	
			.16	bistable	
			.20	bistable	
0.9	.05	85	0	limiter	77
			.04	clipper	
			.12	AC gain	
			.16	AC gain	
			.20	AC gain	

A laser tunable over the absorption width of the R_1 line of ruby (o.5 cm^{-1} total width) was required to study the above-described ruby device. Monochromatic cw power of several milliwatts was required. Dye laser efficiencies in the requisite spectral region are low and for this reason, as well as for greater stability, a ruby laser was used. The argon laser-pumped cw ruby laser is shown in Figure 3.

In contrast to earlier designs the output of this laser is antiparallel to the pump beam. The ruby element 101 has faces which form a wedge of wedge angle 12 seconds± 2 seconds of arc (exaggerated in the figure). The element is a 1/4 inch diameter, 1 cm long, .05% Cr^{3+} concentration, 60 degree, Union Carbide ruby rod with faces flat to $\lambda/10$. The upper face of the ruby rod is maintained within a vacuum supported by the chamber 102. The lower face of the ruby rod is maintained at approximately liquid nitrogen temperature by means of the dewar 103. The liquid nitrogen ruby face was coated for 99%+ reflectivity at 5145 Angstroms and 6934 Angstroms. The vacuum ruby face had 50% reflectivity at 6934 Angstroms and was 3% reflective at 5145 Angstroms. The rod was held in a 0.255 inch i.d. hole in a Varian CONFLAT flange 104 and epoxied in place using Stycast 1266 epoxy (STYCAST is a registered trade mark). The flange 104 was mounted on a 1½ inch i.d. evacuated stainless steel tube with a window 105 at Brewster's angle. A VacIon vacuum pump provided pressures of 10^{-4} Torr and was chosen to avoid oil condensation on the cold ruby face in the vacuum region.

The output frequency of the ruber laser depended on the temperature of the liquid nitrogen in contact with the ruby, which was controlled by pumping on or pressurizing the nitrogen gas 111 above the liquid nitrogen. The pumping and pressurizing means are now shown. To lengthen the filling cycle time of the dewar a helium balloon 106 -- a hollow cylinder with an open bottom which was pressurized with gaseous helium -- was used allowing the liquid nitrogen level 108 in the dewar to be raised, lowered, or maintained, at will.

The argon laser beam at 5145 Angstroms provided a power of 2 W at the ruby rod. The beam was focused by a 15 cm lens 107 into the ruby laser rod. All of the optics were antireflection coated or at Brewster's angle. The approximately 300 mW ruby output was a linearly polarized single transverse mode. A collimating lens (not shown) provided a 2.45 diameter beam. The output contained a number of longitudinal modes separated by approximately 8.6 GHz, the free spectral range (C/2NL) of the 1 cm long cavity. The modes span a frequency range of more than 60 GHz about the LN_2 PR_1 line.

Although the laser output had a number of longitudinal modes a single mode could be made to dominate by bringing different parts of the wedged laser rod under the pump beam. For this reason the laser assembly was on an XY translator 109. By pumping or pressurizing the dewar the temperature of the liquid nitrogen, and the ruby element and consequently the frequency of the dominant mode, could be tuned over a 20 GH_z range.

A single output frequency was obtained using an external Fabry-Perot interferometer 100 (Burleigh RC 19) to filter the ruby laser output. The output of the ruby laser was directed to the Fabry-Perot by the mirror 110. The Fabry-Perot had 95% reflective coated $\lambda/100$ flat mirrors separated by about 2mm with a free spectral range of 75 GH_z. The Fabry-Perot spacing was controlled by piezoelectric transducers on one of the mirrors. Using a small 400 Hz modulation on the d.c. bias on the transducers, the output of the Fabry-Perot was maintained at a local Fabry-Perot output intensity maximum corresponding to being resonant with any given mode. A standard servotechnique was used for this purpose. There was a 25% transmission loss in the Fabry-Perot due to absorption in the coatings and surface irregularities in the mirrors.

The ruby laser delivered more than 300 mW of power distributed among 7 or 8 different modes. By tuning the ruby wedge, more than 75 mW was obtained in any one of several filtered single modes. By sweeping the Fabry-Perot through a free spectral range and passing the light through a ruby absorber we could see the relative absorption of the different modes directly. The absolute frequency was measured with a high resolution grating spectrometer, but the mode frequencies relative to one another were measured with respect to a helium neon laser using a Fabry-Perot. The helium neon laser line was also used to make sure that the same order of the Fabry-Perot was always being used. An optical isolator 112 was used on the laser output in the optical amplifier configuration of Figure 2.

2. *Gallium Arsenide (GaAs)*

A device capable of operating in either the bistable or amplifying mode may be fabricated using GaAs as the nonlinear medium. In such a device light of approximately 10^4 cm^{-1} induces transitions which populate excited states with which states there are associated excitons. An exciton is a bound electron hole pair and more generally may be considered as a neutral excited mobile state of a crystal. The energy of the excition is just below that of the conduction band and hence contributions from this band and from other nondriven states play a significant role in determining the ultimate value of the nonlinear dispersion. In addition, in this system as in semiconductors generally, the change of wave function in the excited state alters the matrix elements which determine dispersion thereby furthe effecting the dispersive contributions to the amplification phenomenom.

The GaAs device consists of a GaAs medium placed within an optical cavity. The input optical power, intensity, wavelength, dopant concentration and thickness of the nonlinear medium are adjusted along with other parameters such that the dispersive properties of the medium dominate or are equal to its absorptive properties and combines with the cavity properties to yield either bistability or amplifications. Sandwich structures with $GaAl_yAs_{1-y}$ on the outside and $GaAl_xAs_{1-x}$ on the inside may be preferred in order to decrease exciton surface decay.

Other Semiconductors

Other semiconductors may also be used as the nonlinear medium in a device such as that described above. Such semiconductors include but are not limited to InP, GaAsSb, and CdS and will show similar optical characteristics. In addition any semiconductor can be doped with impurities to yield impurity levels. The excitation of such impurity levels will introduce dispersive contributions due to non-driven states including the conduction bands. N_2 doped GaP is an example of such a doped semiconductor.

WHAT WE CLAIM IS:-

1. A device for processing optical signals comprising an optical cavity formed by at least two surfaces which reflect light of the wavelength of the optical signals, a non-linear medium within the optical cavity and means for introducing the optical signals into and extracting them from the cavity, the cavity and medium being such as to provide an output intensity/input intensity characteristic having a region exhibiting bistability or differential gain without population inversions being produced in the medium, in which region the dispersive properties of the medium dominate or are equal to the absorbtive properties and the non-linear dispersive properties of the medium include contributions due to non-driven states which are greater than ten percent of the contributions if any due to driven states.

2. A device as claimed in claim 1 wherein the contributions due to non-driven states are greater than fifty percent of the contributions if any due to driven states.

3. A device as claimed in claim 2 wherein the contributions due to non-driven states dominate the contributions if any due to driven states.

4. A device as claimed in any of the preceding claims wherein the coefficient of the term in the field-dependent refractive index which is quadratic in the field is greater in magnitude than $10^{-13}cm^2/statvolt^2$.

5. A device as claimed in any of the preceding claims wherein the driven states include an excited electronic state.

6. A device as claimed in claim 5 wherein absorbtion of light from the optical signal by the medium produces an exciton.

7. A device as claimed in any of the preceding claims wherein the driven states includes an impurity state.

8. A device as claimed in claim 5 or claim 6 wherein the medium is InP, GaAs, GaAsSb or CdS.

9. A device as claimed in claim 5 or claim 7 wherein the medium is ruby.

10. A device as claimed in any of the preceding claims including means for introducing one or more light beams into the cavity in addition to the optical signal.

11. A device substantially as herein described with reference to Figures 1 and 2 of the accompanying drawings.

12. A method of amplifying variations in intensity of an optical signal including introducing the optical signal into the cavity of a device as claimed in any of the preceding claims, the said region of the characteristic exhibiting differential gain and the intensity of the optical signal being within the said region at least some of the time.

13. A method of switching an optical signal between one power level and another including introducing the optical signal into the cavity of a device as claimed in any of claims 1 to 11, the said region of the characteristic exhibiting bistability and the intensity of the optical signal being within the said region at least some of the time, and causing the optical signal to switch between stable portions of the characteristic.

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FIG. 1

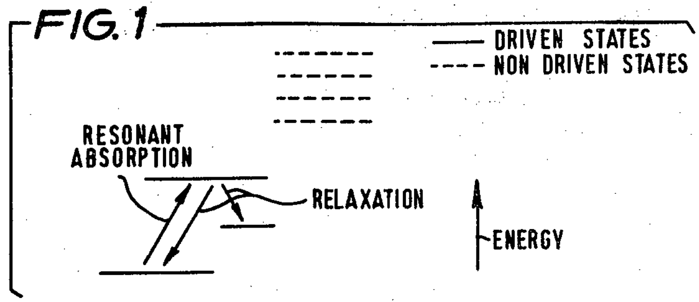

FIG. 2

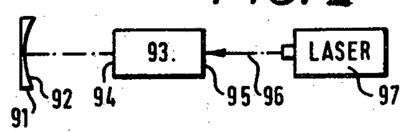

FIG. 3