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PATENT SPECIFICATION

DRAWINGS ATTACHED

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COMPLETE SPECIFICATION

Improvements in or relating to Optical Masers

We, WESTERN ELECTRIC COMPANY INCORPORATED, of 195 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 it is to be performed, to be particularly described in and by the following statement:—

This invention relates to optical masers and, more particularly, to optical masers employing gaseous negative temperature media.

The terms optical maser and laser, used interchangeably hereinafter, refer to devices involving electromagnetic radiation in the infrared, visible, and ultraviolet frequency ranges. This frequency range will be referred to as the optical frequency range.

It is now well known that amplification of electromagnetic wave energy can be achieved by emission of radiation from media in which there is produced a population inversion in a characteristic energy level system. Such media are generally referred to as negative temperature media and the amplification process is termed laser action or, more simply, lasing.

In order for a medium to be useful as a negative temperature medium in an optical maser, it is essential that it be responsive to being pumped; that is, that there be a way to increase the population of the upper energy level of an optically connected pair of energy levels, so that it exceeds the population of the lower energy level of the pair. Numerous arrangements, involving solid state media as well as gaseous media, are now well known.

The fields of application for optical masers, particularly communications, often require continuously operating devices characterized

by a low associated noise level and a high degree of monochromaticity. Due to the relatively more complex crystalline structure of solid maser media, low noise performance has generally heretofore been obtained with gaseous negative temperature media.

However, the output power level of typical gas lasers has been less than generally desired for long distance or high power laser applications.

Additionally, because the power gain per unit length of discharge was low, the prior art gaseous laser structures have been long and cumbersome and, due to the large spacing between the mirrors of the optical cavity, have tended to oscillate at many discrete frequencies simultaneously. In order to reduce the length of the optical cavity and thereby achieve single frequency-operation, the length of the laser tube must be reduced to a few centimeters. Reducing the laser tube length of course reduces the net gain per pass thus making laser oscillation at usable powers difficult to achieve in prior art arrangements.

Several classes of gas lasers are now well known. In each, the amplification process depends upon population inversion achieved through atomic collision in an electrical discharge.

In a first class, the negative temperature medium comprises a single active gas of the noble gas family of helium, neon, argon, krypton and xenon. In a typical noble gas laser, the noble gas atoms are excited by collisions with free electrons in a gaseous discharge. In order for a population inversion to result from electron-atom collisions, it is essential that the active gas atoms have a large cross section for direct electron excitation to the desired upper maser level or to a higher level

which relaxes or decays thereto. It is also necessary that various competing effects produced by the interaction of electrons with the gas be maintained at a relatively low level.

5 Thus pumping of gas lasers by electron-atom collisions requires careful selection of the active gas as well as precise control of environment factors such as pressure, geometry, and discharge intensity. In many cases, more-
10 over, special measures must be taken to inhibit interactions which compete with the desired one.

The selectivity of excitation in a gaseous discharge is enhanced in a second class of
15 lasers by mixing with the active gas an auxiliary gas which has a metastable energy state matching the upper maser level. The auxiliary gas is then excited to its metastable state by electron impact and, through resonant inter-
20 action in inelastic atom-atom collisions, the excitation is transferred to the active gas. In a variation of the technique, the auxiliary gas serves to populate a metastable state of
25 the active gas which has a large cross section for excitation to a desired upper level. Although it is applicable to all combinations of gases which satisfy the particular energy level criteria, the particular selection of usable
30 gases is limited by the close coincidence required of the energy levels between which the excitation transfer occurs.

According to the present invention there is provided an optical maser having a gaseous
35 negative temperature medium within an enclosure, said medium including an active gas and an auxiliary gas in which at least a significant proportion of the auxiliary gas is the He^3 isotope.

Thus we have discovered that the population inversion in a gas laser employing a mixture of an active gas with helium can be significantly increased by substituting the lighter isotope He^3 for the more common isotope
40 He^4 . In accordance with one theory of operation, output power and gain per unit length are increased by the isotope substitution as a result of an increase in the rate at which
45 metastable atoms of the lighter He^3 auxiliary gas are destroyed by collisions with active gas atoms relative to the rate at which metastable atoms of the same auxiliary gas are
50 destroyed by collisions with electrons. With the available power and gain thus increased, laser size can be significantly reduced, permitting substantially single frequency operation.
55

In an interferometer cavity, the reflective surfaces, or mirrors, are positioned with respect to each other and with respect to the
60 negative temperature medium in such a way that light waves are multiply reflected between the cavity extremities, travelling through the active medium on each passage therebetween. During each passage of a wave through
65 the maser medium, it is amplified by interaction with the excited atomic or molecular

resonators therein. On the other hand, energy losses are introduced through scattering inhomogeneities in the medium, through diffraction at the mirror edges, through reflection at each media interface, and through adsorption and transmission at each reflector surface. The practical realization of maser action depends, of course, upon the fact that the associated energy losses can be held to an amount less than the energy gain afforded by the maser medium.

In general, the energy losses introduced by the traversal of media interfaces can be kept to an acceptable minimum by orienting each interface at a particular angle with respect to the plane of incidence of the energy involved. This angle is known in the optical and optical maser arts as the Brewster angle and is defined as the angle whose tangent equals the ratio of the indices of refraction of the medium into which a wave travels over the medium from which it emerges. For energy polarized in the plane of incidence, transmission theoretically occurs without reflection when the Brewster angle condition is met at the frequency of the incident energy. Since the Brewster angle changes very slowly with wavelength, reflection is very small even for surfaces which depart from the Brewster angle by as much as several degrees.

In gas discharge lasers, such as the helium-neon laser, it is frequently possible for population inversion to occur between several lower-state levels and one particularly overpopulated upper-state level. When this condition obtains, laser action can be initiated relatively easily on the strongest transition, but, once oscillation begins, the upper-state is sufficiently depopulated to make laser action on the remaining weaker transitions either extremely difficult or impossible with simple cavity arrangements. It has been priorly suggested that such a condition, which is known in the art as dominance, can be eliminated by introducing a frequency dependent element within the optical maser cavity, thereby making possible selective tuning of the cavity to the weaker transition frequency, simultaneously detuning the cavity for the dominant transition wavelength.

Heretofore, the frequency selective element which has been employed consisted of one or more dispersive prisms inserted within the laser cavity between the negative temperature medium and the external reflectors. Such an arrangement is characterized by considerably increased cavity losses due to the introduction of two additional dielectric interfaces per prism. Although the cavity could be detuned for the dominant transition, such increased losses made oscillation at the weaker transitions extremely difficult.

We have now discovered that the conditions for oscillation at the desired weaker transitions of a laser arrangement can be

selectively imposed by utilizing a reflecting dispersive element as at least one cavity extremity.

5 We have further discovered that a spherical optical maser cavity including a cavity extremity having a Brewster angle refractive surface and a spherical reflecting surface can selectively oscillate on a relatively weak transition. In this connection it is intended that the term spherical cavity refer to any laser cavity in which at least one extremity has a spherical reflecting surface. Well known special cases of spherical cavities are those in which a spherical reflector is spaced away from a plane reflector a distance equal to the focal length of the spherical surface; and confocal, in which a pair of similar spherical reflectors are separated a distance equal to twice their equal focal lengths.

20 We have further found that the beam astigmatism introduced by a spherical reflecting surface of a laser cavity extremity can be compensated by making the refracting surface of the extremity cylindrical. Such astigmatism, if not corrected, can severely degrade laser oscillation.

30 A reflecting prism may be used as a laser cavity extremity and combine the function of a dispersive element with that of a reflector in a single optical structure. A plane reflecting prism can be used with a spherical mirror as the opposite cavity extremity to form an optically resonant cavity within which a suitable negative temperature medium is disposed. Alternatively, the reflecting prism can have a spherical reflecting surface, the refracting Brewster angle surface of the prism being configured to have a concave cylindrical curvature.

40 The invention will now be described with reference to the accompanying drawings, in which:

45 FIGS. 1 and 2 are longitudinal cross-sectional views of optical masers in accordance with the invention;

FIG. 3 is an energy level diagram helpful in understanding the invention;

50 FIG. 4 is a graphical illustration of the improvement in output power afforded by the invention;

FIG. 5 is a schematic view of an optical maser arrangement employing a plane reflecting prism; and

55 FIGS. 6A and 6B are different views of a spherical reflecting prism useful in the arrangement of FIG. 5.

60 Referring now to the drawing in greater detail, FIGS. 1 and 2 illustrate, in longitudinal cross section, optical masers 10 and 20 respectively, comprising an enclosing tube 11, which can be of quartz, containing a mixture of an active gas, neon, and an auxiliary gas, helium. These gases are characterized by energy levels which are critically related in a manner to be pointed out in detail herein.

after. The helium gas is substantially pure He^3 . He^3 is a non-radioactive helium isotope produced as a by product in atomic reactors and having an atomic weight of 3, as contrasted with the naturally occurring He^4 isotope found in nature and having an atomic weight of 4.

The helium concentration can correspond, for example, to a partial pressure of 0.7 Torr and the neon concentration to a partial pressure of 0.1 Torr. It is generally desirable that the partial pressure of helium exceed that of neon although laser action can occur with helium-neon ratios differing considerably from 7 to 1. For example, the optical maser is operative over a broad range of partial pressures, from 3 to 1 to 50 to 1, although the intensity of stimulated emission is not constant over this range. C. K. N. Patel presents measurements of power output versus various gas pressures in the He^4 -Ne laser in an article beginning at page 3194 of Volume 33 of the Journal of Applied Physics, November 1962. Similar relative performance, with higher gain per unit length, is exhibited by a similar He^3 -Ne laser. The amount by which the gain and power output are increased by the substitution of He^3 for He^4 is proportional to the amount of He^4 for which He^3 is substituted. Thus in a gas mixture containing neon with helium in which 50 per cent is He^3 and 50 per cent is He^4 , the improvement in gain and power output is approximately one half that realizable for a 100 per cent He^3 substitution. In general, however, it is necessary only to have a significant amount of He^3 present in the gas mixture to achieve gain and power output improvement. Typically, the proportion of He^3 would exceed the proportion of He^4 . In the preferred embodiment, the gas mixture would comprise neon with substantially 100 per cent He^3 .

Encircling tube 11 in FIG. 1 are a plurality of electrodes 12 which are connected to a radio-frequency source 13 for providing energy to excite an electrical discharge through the active medium. A convenient frequency is about 25 megacycles, although it is to be understood that this is not critical and can be varied over an extremely wide range. Advantageously, the pump energy is of a frequency easily controlled and readily available at sufficient power levels to produce a discharge inside the tube 11, the walls of which should therefore be substantially transparent to such energy. Alternatiely, microwave pump energy may be coupled to the active medium by means of a cavity, not shown in the drawing, resonant at that frequency and enclosing the gas filled tube. As illustrated in FIG. 2, a discharge can also be excited in the gaseous active medium by means of a direct current voltage applied from d-c source 24 through current limiting resistor 25 between electrodes included within the tube 11, such

as electrodes 22. The electrodes 22 are housed in projections 23 which extend from the side of tube 11, thereby avoiding any obstruction of the light beam path along the axis of the tube. Furthermore, the projections 23 tend to trap any material evaporated or sputtered from the electrodes 22 which might otherwise contaminate the inside surfaces of tube 11. In both FIGS. 1 and 2, the ends of tube 11 comprise transparent windows 14 which define a light beam path through the active medium. To reduce reflections at the windows, they are inclined at Brewster's angle to the beam path.

It is characteristic of helium that its energy level system includes a large number of levels, only a small relevant portion of the system being shown in FIG. 3. For example, it is characteristic of the level corresponding to the 2^1S state (in the LS designation), that it is metastable. As the term is understood in the art, this means that the time takes an atom in the 2^1S state to relax to the ground state E_0 is relatively long or, viewed differently, that the probability of the transition from the 2^1S state to ground state is small. On the other hand, the rate of decay between the higher levels E_2, E_3 to the 2^1S level is large so that there is a tendency for atoms in such higher levels to decay to 2^1S either by a direct transition as a result of collisions or in cascade fashion as a result of successive transitions. The net effect is an accumulation of atoms at the 2^1S level. The principal counter-effect is a decay of atoms from this level to the ground state as a result of collisions with the tube surfaces. However, it is possible by the application of sufficient radio-frequency or other energy to the helium to produce sufficient energetic free electrons for collisions with helium atoms to increase the population of helium atoms in the 2^1S level to a relatively high value.

As mentioned above, in a preferred embodiment tube 11 also includes neon gas. The relevant portion of the energy level system of neon also is depicted in FIG. 3. For example, neon includes four energy levels, $3s_2, 3s_1, 3s_0$, and $3s_{-1}$ (in Paschen notation) whose separations from the ground state E_0 substantially match the separation between levels E_0 and 2^1S of helium. Moreover, neon also includes 10 energy levels, $2p_1, \dots, 2p_{10}$, which are between level E_0 and the $3s$ levels and whose separations from such higher levels correspond to wavelengths in the visible optical range.

It is characteristic of a system of the kind described that the energy level $3s_2$ of the active gas will reach close to thermal equilibrium with energy level 2^1S of the auxiliary gas because each corresponds to essentially the same energy. Thus a large cross section will exist for inelastic collisions resulting in an exchange of energy between the 2^1S level of helium and the $3s_2$ level of neon. This

exchange results in the neon population of the $3s_2$ level particularly increasing to the point at which its proportion of the total neon population will substantially match the proportion of 2^1S helium in the total helium population. Due to the adiabatic nature of the collisions, the levels of the neon atoms, such as $2p_1$, which differ in energy appreciably from that of the metastable level of the helium, are not directly affected. As a consequence, a negative temperature, or population inversion, can be established between the $3s$ and $2p$ levels. The separation of these two levels has a wave number of about 15,800 corresponding to a wavelength of about 6,328 angstroms.

In accordance with the maser principle it is known that when a negative temperature population inversion is established between a pair of energy levels in a medium, emission may be stimulated therefrom at a wavelength corresponding to the energy separation between the inverted levels. Stimulated emission occurs when radiation of the appropriate frequency is incident on the active medium and induces the excited particles to undergo transitions from the upper to the lower energy state. The emitted radiation, indicated by arrow 30, is coherent and in phase with the stimulating signal. In the absence of an externally applied signal, emission may be stimulated by photons emitted spontaneously by some of the excited particles as they relax to the lower energy level. In either case, the stimulated emission adds to the stimulating wave so that the signal experiences gain or amplification as it travels through the medium. The amount of the amplification is exponentially related to the length of the ray path in the medium and inversely proportional to its diameter. The elongated geometry of a typical optical maser tends to establish a preferred direction, e.g. the axial direction, such that photons spontaneously emitted in that direction undergo substantially greater amplification than photons emitted in off-axial directions. Thus, the energy emitted from an end of tube 11 is substantially monochromatic and coherent. It will be apparent that the device can be employed either as a source of such energy, or as an amplifier of externally applied signals.

According to one theory the available output power is increased because the presence of the He^3 isotope in the gas mixture causes a higher electron temperature condition to obtain as reflected in the increased discharge voltage gradient. In the presence of the higher electron temperature the rate at which helium atoms are excited to the 2^1S level is increased, thereby increasing the population of the 2^1S level. Additionally, the rate at which collisions occur between helium atoms at the 2^1S level and neon atoms at the ground state, thereby raising the latter to the $3s_2$ state

from which emission at the desired frequency can be stimulated, is increased; while the rate at which collisions occur between helium atoms at the 2'S level and excited electrons in the discharge, thereby causing the helium atoms to fall once again to a ground state without transfer of energy to the active neon gas, is either reduced or increased by a lesser amount.

To make it possible for the energy emitted to reach greater intensity and to encourage coherent emission, it is desirable that there be favoured the buildup of oscillations of the frequency corresponding to the separation between levels 2p₁ and 3s₂.

To this end, reflective plates 15 and 16 are positioned at opposite ends of the envelope 11 in FIGS. 1 and 2 adjacent the windows 14 thereby enabling standing waves of the oscillatory energy to be set up between them. As is characteristic, such plates are made to be highly reflective of the energy of the wavelength of interest while absorbing as little as possible and transmitting a small portion of such energy. In particular, their thickness is preferably made such that the reflections at the two faces add in phase for the wavelength of interest. Ordinarily, it is more convenient from the standpoint of adjusting their separation for optimum results that the reflective plates be separate elements as shown. Alternatively, either or both of such elements may be positioned inside the envelope or incorporated as an end plate thereof. As with the device operating without mirrors, the optical maser utilizing a cavity resonator is capable of acting as either a generator or an amplifier.

The increased power output, or gain provided by the He³ substitution permits the length of the cavity between end reflectors 15, 16 and therefore the length of tube 11 to be reduced from the typical prior art length of one meter by a factor 18 without destroying the necessary oscillation condition. At the same time, the radial dimension of tube 11, typically 6 millimeters in prior art tubes, is reduced by a factor of 6. The resultant arrangement, in which tube 11 typically has a length of two inches and a diameter of one millimeter, is readily adaptable to a host of practical uses, both in the laboratory as a research tool and in commerce as a compact coherent energy source in optical, metrological, and communications applications.

In addition to and as a result of, the reduced physical size, fewer discrete frequencies of oscillation are emitted in the smaller multimode cavity arrangement. Oscillation at a single discrete frequency, tunable over a 1500 megacycle range centred at 4.73×10^{14} cps, has been attained by varying slightly the optical path length between the mirrors. The total mechanical motion required to tune over the entire range is less than .000012 inch. Thus, by connecting one laser extremity to a positioning device and monitoring the fre-

quency of the laser output, minute position differentials can be detected. Other methods of tuning, involving an electronically variable path length for example, are also possible.

Measurements of the output of gaseous optical masers employing mixtures of neon and He³ have been made, and one resultant plot appears in graphical form as FIG. 4. The measurements were carried out with a standard one meter long, 6 millimeter inside diameter, d-c excited laser tube provided with quartz Brewster angle output windows. The gases which produced curve 41 in FIG. 4 were spectroscopic grade neon and spectroscopic grade He³. For curve 42, identical neon was mixed with 99 per cent He³ in 99.8 per cent helium, such as that obtainable from Monsanto Research Corporation, Miamisburg, Ohio. Both helium gases exhibited essentially the same spectrum with no indication of impurities other than a possible trace of neon. With partial pressures of 0.1 Torr neon and 0.5 Torr helium, the power output of all modes was measured as a function of discharge current. Curve 42 in FIG. 4 shows an increased power output of over 25 per cent over that of curve 41 at maximum output. Subsequent test runs in small lasers have consistently produced output power increases of 50 per cent and, at single values of discharge current, power increases up to 100 per cent have been observed.

Due to the relatively small amount of helium gas required, the increase in cost of materials to realize the substantial power increase is minimal. The resultant reduction in physical size permitted by the substitution may actually reduce material costs below those of the prior art. The preferred form of gaseous optical maser described may be modified to utilize different gases as the active gas with He³ as the auxiliary gas. For example, it is feasible to employ xenon typically at a pressure of 10⁻³ Torr and helium at a pressure of 1 Torr, or mercury vapour at a pressure of about 10⁻³ Torr and helium at a pressure of 1 Torr.

In the embodiment of the invention shown in FIG. 5, the energy beam, typified by ray 56, is reflected back and forth along axis 54 between reflecting means 52 and 53, growing in intensity upon each traversal of the negative temperature medium. Each passage of energy beam 56 between the external reflectors involves a traversal of output windows 57, 58 of envelope 64, which can comprise plane sheets of high quality homogeneous optical grade glass, or fused quartz such as Corning (Registered Trade Mark) No. 7940, and which are inclined at the Brewster angle to axis 54 and to beam 56. For certain applications, windows 57, 58 can comprise plano-convex or convexo-convex lenses. Windows 57, 58 are sealed to the envelope containing the negative temperature medium 51, advantageously by a

procedure involving thermal fusion of their contacting surface portions.

5 Reflecting means 52 comprises a spherical reflector, which can comprise a dielectric or metallic base having a metallic reflecting surface or a multiple layer dielectric coating. For operation as a hemispherical cavity, the focal length of mirror 52 is equal to the spacing between the reflecting surfaces of reflectors 52 and 53.

10 Reflecting means 53 comprises a dielectric prism having a beam refracting surface 59 disposed at the Brewster angle with respect to incident energy beam 56 and a beam reflecting surface 60 orthogonally disposed with respect to beam 56', which corresponds to beam 56 after refraction. Prism 53 can comprise fused quartz or optical quality glass, and has a conventional 13, 15 or 17 layer reflecting coating 61 disposed upon reflecting surface 60. As a typical example, coating 61 can comprise alternate layers of magnesium fluoride and zinc sulfide, each approximately one quarter wavelength thick at the desired frequency of operation.

25 As stated hereinbefore, typical gaseous optical maser media are characterized by a plurality of energy levels. Frequently, maser transitions occur between a common upper level and several lower levels, each transition producing radiation of a different frequency. In general, one of the transitions is dominant with respect to the other and, once emission is stimulated at the dominant frequency, the upper states are depopulated sufficiently to render sustained oscillation via the weaker transitions extremely difficult. As is illustrated in FIG. 5, prism 53 is characterized by a frequency dependent dispersive effect which results in an incident collimated beam containing a plurality of frequency components being decollimated; or diverged upon entering the prism. Thus the shorter wavelength beam portions 62 are refracted at a greater angle than desired wavelength portion 56', while longer wavelength beam portions 63 are refracted at a lesser angle than portion 56'. Upon reaching reflecting surface 61, beam portions 62, 63 are reflected thereby away from the axis of the medium and cavity at an angle equal to their respective angles of incidence. Any beam portions which are no longer parallel to the beam axis 56 are, either immediately or after several reflections, lost from the laser cavity. By rotating prism 53 about an axis normal to the plane of the drawing, the laser cavity can be tuned to any one of the radiating transitions with concomitant detuning of adjacent unwanted transition frequencies.

60 The particular structure of FIG. 5 thus combines the functions of a dispersive tuner and a reflector in a single element. Such an arrangement possesses several important advantages over the multiple element structure of

the prior art, among which are a permanent protection of the initial, critical layers of the dielectric reflecting coating, lower cavity losses resulting from the elimination of at least two air to dielectric interfaces, and the ready accessibility of the reflecting surface for external energy extraction, mode selection, and impedance matching purposes. In addition, the beam portion 56' is reflected back upon itself for normal incidence upon layers 61, thus preserving laser action without the inconvenience of lateral beam shifting present in total internal reflection arrangements.

The above description of FIG. 5 has been given with respect to a laser cavity in which a spherical mirror and a plane reflector form the cavity extremities. In many cases, it is desirable that the laser cavity be confocal; i.e., that both reflectors be spherical, with radii of curvature equal to their separation. The desirability of the confocal, or near confocal, condition, arises from the direct proportionality between laser medium gain and its length and the converse proportionality between the laser medium gain and its diameter. It follows that narrow laser tubes are most efficient. Thus the desired beam is a narrow pencil beam, a condition best obtained in a confocal laser cavity environment. Reflecting surface 60 of prism 53 of FIG. 5 can be made spherical with appropriate radius of curvature without destroying the frequency selective nature of the dispersive-reflective prism. However, such a combination of a prism and a spherical reflecting surface is astigmatic and therefore causes the laser beam to have a different wavefront curvature in each of the two principal planes. Such a laser beam is undesirable for most purposes since the quality or Q factor for low order modes of the laser cavity resonance for such a beam is reduced, thus making oscillation on weak transitions very difficult.

The beam astigmatism of a spherical reflecting prism may be eliminated by making the refracting surface thereof concave cylindrical. An understanding of this can be more readily gained from reference to FIGS. 6A and 6B of the drawing.

In FIG. 6A, a meridional plane view of an astigmatism compensated spherical dielectric reflecting prism 70 is shown; and in FIG. 6B, a sagittal plane view of prism 70 is shown. By way of definition, the meridional plane is the plane of the drawing in FIG. 5 and the sagittal plane is a plane normal to the meridional plane and containing the normal to the spherically curved surface, that is, beam portion 56'. The input ray axis is collinear with U_{mer} , the optical radius of curvature of prism 70 in the meridional plane; and U_{sag} , the optical radius of curvature of the prism in the sagittal plane. The ray is incident at an angle β and is refracted at surface 71 at an angle ϕ .

The general expressions for the refraction of a thin astigmatic pencil of rays at a surface with arbitrary curvature in two principal planes, as given by Born and Wolf in

"Principles of Optics", Chapter 4. (1959), can be rewritten in the environment of FIGS. 6A and 6B as

$$\frac{1}{U_{\text{mer}}} - \frac{n}{S_{\text{mer}}} \frac{\cos^2 \phi}{\cos^2 \beta} = \frac{1}{R_{\text{mer}}} \left(\frac{1}{\cos \beta} - \frac{n \cos \phi}{\cos^2 \beta} \right) \quad (3)$$

and

$$-\frac{1}{U_{\text{sag}}} + \frac{n}{S_{\text{sag}}} = \frac{n \cos \phi - \cos \beta}{R_{\text{sag}}} \quad (4)$$

where R_{mer} and R_{sag} are the geometrical radii of curvature of the refracting surface, S_{mer} and S_{sag} are the geometrical radii of the reflecting surface of the prism in the meridional and sagittal planes, respectively, and n is the index of refraction of the prism. It is assumed in this analysis that one of the principal planes of the ray pencil coincides with one of the principal planes of curvature of the prism.

The criterion for stigmatic imaging is that $U_{\text{mer}} = U_{\text{sag}} = U$, which implies that a point source located at U will be imaged by the optical system at U . Thus, U becomes the optical centre of curvature of the reflecting prism. By properly choosing R_{sag} and R_{mer} , the reflecting prism can be made stigmatic for arbitrary choice of S_{sag} and S_{mer} . In the specific case of interest, the reflecting surface is made spherical, and therefore $S_{\text{sag}} = S_{\text{mer}} = S$; and R_{sag} is made infinite. Solving the modified Born and Wolf equations for R_{mer} ,

$$R_{\text{mer}} = \frac{\frac{1}{\cos \beta} - \frac{n \cos \phi}{\cos^2 \beta}}{\frac{n}{S} \left(1 - \frac{\cos^2 \phi}{\cos^2 \beta} \right)} \quad (5)$$

In the present case β is the Brewster angle of incidence and equation (5) therefore reduces to

$$R_{\text{mer}} = \frac{S}{n \cos \beta} \quad (6)$$

the condition for stigmatic imaging by prism 30, with an optical radius of curvature $U = S/n$. It is thus evident that the astigmatism of an uncorrected spherical reflecting prism used as one reflector in a confocal laser cavity can be eliminated by making the refracting surface of the prism cylindrical in accordance with equation (6).

A comparison of the focal images formed by an uncorrected spherical reflecting prism and by one corrected for astigmatism has been made.

For the uncorrected prism, $S = 3.9$ meters, $n = 1.458$, and $R_{\text{mer}} = R_{\text{sag}} = \infty$; while for the corrected prism, $S = 3.9$ meters, $n = 1.458$, $R_{\text{sag}} = \infty$, and $R_{\text{mer}} = 4.7$ meters. A laser beam, diverging from a point approximately 2.7

meters from the prism surface illuminated the prisms. The meridional focus, at 0.9 meters; and the sagittal focus, at 2.8 meters; for the uncorrected prism showed elongations characteristic of astigmatic optical elements. Conversely, the image formed by the corrected prism was very nearly circular at all points in the image space.

Experimentally, using a laser cavity with one reflecting prism extremity and one spherical mirror extremity, transitions at 6118 Å and 6401 Å have been made to oscillate. In addition, oscillation at many priorly observed transitions at infrared frequencies has been demonstrated.

While the above disclosure of cavity lasers has been particularly described with reference to a combination of one reflecting prism and one spherical mirror, in many cases, it may be desirable to utilize reflecting prisms at both cavity extremities, oriented with either cumulative or noncumulative dispersive effect.

Reflecting prisms and He³ substitution have been found particularly useful in obtaining oscillations on the weakest $3s \rightarrow 2p$ visible transitions in the helium-neon laser. For example, laser transitions at 6046 Å and 5940 Å have been made to oscillate in a 1.2 meter, 4 millimeter I. D. laser tube with a pair of reflecting prisms but not with any other available reflector combinations. The same tube when used with a 15 layer reflecting prism and a 13 layer spherical mirror, rather than a second reflecting prism, has an output power of over 40 milliwatts at the dominant 6328 Å.

WHAT WE CLAIM IS:—

1. An optical maser having a gaseous negative temperature medium within an enclosure, said medium including an active gas and an auxiliary gas, in which at least a significant proportion of the auxiliary gas is the He³ isotope.

2. An optical maser according to claim 1, in which the amount of the He³ isotope is greater than the total of other helium isotopes present.

3. A maser according to claim 1 or 2, in which the active gas is neon.

4. A maser according to claim 1, 2 or 3,

The general expressions for the refraction of a thin astigmatic pencil of rays at a surface with arbitrary curvature in two principal planes, as given by Born and Wolf in

"Principles of Optics", Chapter 4 (1959), can be rewritten in the environment of FIGS. 6A and 6B as

$$\frac{1}{U_{\text{mer}}} - \frac{n}{S_{\text{mer}}} \frac{\cos^2 \phi}{\cos^2 \beta} = \frac{1}{R_{\text{mer}}} - \left(\frac{1}{\cos \beta} - \frac{n \cos \phi}{\cos^2 \beta} \right) \quad (3)$$

and

$$\frac{1}{U_{\text{sag}}} + \frac{n}{S_{\text{sag}}} = \frac{n \cos \phi - \cos \beta}{R_{\text{sag}}} \quad (4)$$

where R_{mer} and R_{sag} are the geometrical radii of curvature of the refracting surface, S_{mer} and S_{sag} are the geometrical radii of the reflecting surface of the prism in the meridional and sagittal planes, respectively, and n is the index of refraction of the prism. It is assumed in this analysis that one of the principal planes of the ray pencil coincides with one of the principal planes of curvature of the prism.

The criterion for stigmatic imaging is that $U_{\text{mer}} = U_{\text{sag}} = U$, which implies that a point source located at U will be imaged by the optical system at U . Thus, U becomes the optical centre of curvature of the reflecting prism. By properly choosing R_{sag} and R_{mer} , the reflecting prism can be made stigmatic for arbitrary choice of S_{sag} and S_{mer} . In the specific case of interest, the reflecting surface is made spherical, and therefore $S_{\text{sag}} = S_{\text{mer}} = S$; and R_{sag} is made infinite. Solving the modified Born and Wolf equations for R_{mer} ,

$$R_{\text{mer}} = \frac{\frac{1}{\cos \beta} - \frac{n \cos \phi}{\cos^2 \beta}}{\frac{n}{S} - \frac{\cos^2 \phi}{\cos^2 \beta}} \quad (5)$$

In the present case β is the Brewster angle of incidence and equation (5) therefore reduces to

$$R_{\text{mer}} = \frac{S}{n \cos \beta} \quad (6)$$

the condition for stigmatic imaging by prism 30, with an optical radius of curvature $U = S/n$. It is thus evident that the astigmatism of an uncorrected spherical reflecting prism used as one reflector in a confocal laser cavity can be eliminated by making the refracting surface of the prism cylindrical in accordance with equation (6).

A comparison of the focal images formed by an uncorrected spherical reflecting prism and by one corrected for astigmatism has been made.

For the uncorrected prism, $S = 3.9$ meters, $n = 1.458$, and $R_{\text{mer}} = R_{\text{sag}} = \infty$; while for the corrected prism, $S = 3.9$ meters, $n = 1.458$, $R_{\text{sag}} = \infty$, and $R_{\text{mer}} = 4.7$ meters. A laser beam, diverging from a point approximately 2.7

meters from the prism surface illuminated the prisms. The meridional focus, at 0.9 meters, and the sagittal focus, at 2.8 meters, for the uncorrected prism showed elongations characteristic of astigmatic optical elements. Conversely, the image formed by the corrected prism was very nearly circular at all points in the image space.

Experimentally, using a laser cavity with one reflecting prism extremity and one spherical mirror extremity, transitions at 6118 Å and 6401 Å have been made to oscillate. In addition, oscillation at many priorly observed transitions at infrared frequencies has been demonstrated.

While the above disclosure of cavity lasers has been particularly described with reference to a combination of one reflecting prism and one spherical mirror, in many cases, it may be desirable to utilize reflecting prisms at both cavity extremities, oriented with either cumulative or noncumulative dispersive effect.

Reflecting prisms and He³ substitution have been found particularly useful in obtaining oscillations on the weakest 3s₂ → 2p visible transitions in the helium-neon laser. For example, laser transitions at 6046 Å and 5940 Å have been made to oscillate in a 1.2 meter, 4 millimeter I. D. laser tube with a pair of reflecting prisms but not with any other available reflector combinations. The same tube when used with a 15 layer reflecting prism and a 13 layer spherical mirror, rather than a second reflecting prism, has an output power of over 40 milliwatts at the dominant 6328 Å.

WHAT WE CLAIM IS:—

1. An optical maser having a gaseous negative temperature medium within an enclosure, said medium including an active gas and an auxiliary gas, in which at least a significant proportion of the auxiliary gas is the He³ isotope.

2. An optical maser according to claim 1, in which the amount of the He³ isotope is greater than the total of other helium isotopes present.

3. A maser according to claim 1 or 2, in which the active gas is neon.

4. A maser according to claim 1, 2 or 3,



in which two optically reflecting members define a light beam path through said enclosure to form a resonant interferometer cavity for the coherent radiation emitted by the active gas.

5 5. A maser according to claim 4, in which the length of the light beam path between said reflecting members is of the order of two inches.

10 6. A maser according to claim 5, in which said enclosure confines said negative temperature medium within a radius of one millimetre in a direction normal to said path.

15 7. A maser according to claim 4, 5 or 6, in which at least one of said reflecting members is dispersive.

20 8. A maser according to claim 7, in which said dispersive reflecting member comprises a dielectric prism having a first surface at which light is refracted and a second surface at which light is reflected, said second surface being disposed orthogonally with respect to light of a selected frequency in said beam which is incident upon said second surface.

25 9. A maser according to claim 8, in which said second surface is spherical.

10. A maser according to claim 8 or 9, in which said first surface is cylindrical, and in which said light beam is incident thereon at the Brewster angle.

11. A maser according to claim 10 as appended to claim 9, in which the radius of curvature R of said first surface is equal to S

where S is the radius of curvature of said second surface, n is the index of refraction of said prism, and β is the Brewster angle.

12. An optical maser arranged substantially as herein described with reference to and as shown in FIG. 1, FIG. 2, or FIG. 5 with or without the modification of FIGS. 6A and 6B, of the accompanying drawings, having an auxiliary gas He^3 .

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