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ABSTRACT

A concept is described whereby simultaneous independent oscillation may be obtained at slightly different frequencies on two orthogonally linearly polarized modes of the same laser cavity. It involves simply replacing one of the end mirrors with a suitable diffraction grating, reflecting in zeroth order. Experiments on an HCN laser ($\lambda \doteq 337\mu m$) show that the technique works successfully, though only on certain of the transverse modes; mode structure analysis has been performed to show which modes are involved. Polarization modulation at the difference frequency of 0.9MHz, determined by the choice of grating, has been observed; its frequency stability is fully adequate for heterodyne interferometry or similar purposes. The technique should be applicable to other lasers.

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Introduction

In interferometry, scattering and similar remote probing experiments it is often desirable to use a reference beam whose frequency differs from that of the probe beam. Such an arrangement, constituting a 'heterodyne' system in which single-sideband detection is used, enables the direction of phase shift (or equivalently of frequency shift) of the probe beam to be determined unambiguously. By contrast, a 'homodyne' system in which reference and probe beams have the same frequency, can resolve the directional ambiguities only by adopting more complicated mixing schemes providing signals in phase-quadrature [1], for which the spectral analysis can be considerably more elaborate [2].

The minimum frequency difference required for a heterodyne system is in general equal to the maximum frequency of interest in the phase shift of the probe beam. If this frequency is sufficiently low, mechanical modulation techniques may be applicable. However in many cases frequencies up to 1 MHz and beyond are of interest and more sophisticated methods are called for.

In the visible and infrared out to beyond 10 μm wavelength, electro-optic modulators are available to shift the frequency of the reference beam allowing a single frequency laser source to be used. In microwave systems, techniques are also available for frequency shifting. However in the submillimetre wave region, which is of particular relevance for plasma physics experiments, efficient solid state modulators are not available.

Two different systems have been successfully developed for submillimetre heterodyne interferometry. The first [3] uses a rotating grating and the Doppler effect to shift the frequency of the laser beam. Its primary limitation appears to be that a typical frequency shift is ∿ 10 kHz and while this may in principle be increased by increasing rotation speed or by multiple reflections, there are clear limitations to this extrapolation. The second [4] uses two completely separate lasers for the reference and probe arms which may be detuned to give a frequency difference of 1 MHz or more. The major drawback here is the additional complexity of an additional laser and all the difficulties of accurately stabilising the cavities.

The present work describes a technique for obtaining simultaneously from a single laser cavity two beams differing in frequency by an amount somewhat smaller than the laser transition line width (typically $\gtrsim$ 1 MHz). These two modes are linearly polarized orthogonal to each other and hence may easily be separated outside the laser by a polarizer to form the reference and probe beams of an interferometer or scattering experiment. The technique has been applied to a waveguide HCN laser and proves to be simple and highly efficient.

The Concept

In a submillimetre laser such as the HCN laser the mode separation even of the different transverse modes [5] is larger than the linewidth of the transition. For this reason the laser operates on essentially a single mode. Typically there is a degeneracy between modes having orthogonal polarizations but the same mode numbers and usually this degeneracy is broken by introducing anisotropies in the loss of the cavity, either accidentally or deliberately, which favour one polarization. Thus for example even a few parallel wires in the cavity can cause the electric field polarization to align itself perpendicular to the wires. If, however, the polarization degeneracy is broken by introducing an anisotropy in the phase (i.e. the effective cavity length) then the possibility exists for the laser to oscillate simultaneously on orthogonal polarizations at different frequencies.

Consider a laser of cavity length L wavelength $\lambda = c/\nu$ where c is the velocity of light (in the laser medium) and ν the laser frequency. If $\Delta\nu_t$ is the linewidth of the transition and ΔL the difference in effective cavity length for either polarization then a necessary condition for simultaneous oscillation is

$$(\Delta L - n\lambda/2)/L \lesssim \Delta\nu_t/\nu \tag{1}$$

where n is an integer included to indicate that ΔL can be more than one half wavelength if necessary. We shall for simplicity take $n = 0$ from here on but it should be understood that other values are possible. For the HCN laser $\nu = 890$ GHz $\Delta\nu_t \sim 5$ MHz so $\Delta L/L \lesssim 5 \times 10^{-6}$; e.g. if $L = 3$m $\Delta L \lesssim 15$ µm.

I have shown elsewhere [6] that the effect of a diffraction grating, whose ruling spacing is shorter than half a wavelength, upon radiation reflected from it is to introduce a phase shift between the two characteristic polarizations equivalent to a difference in effective position of reflection of typically ∿ 20% of the groove depth. Therefore if one of the end mirrors of the laser cavity is replaced with an appropriate grating, the effective cavity length change required by eq(1) may be produced. The advantage of this technique of introducing the phase anisotropy is that it is essentially lossless insofar as the grating may be taken as perfectly conducting and also the ΔL introduced is very stable since it depends only upon the structure of the grating grooves. Note that this is a completely different application of a grating from that commonly used to obtain single prefered frequency operation of e.g. CO_2 lasers, where the grating is used in non-normal incidence and typically first order. Here we are referring to normal reflection in zeroth order, all other orders being evanescent. The grating is just acting as a plane mirror.

Of course the introduction of a phase anisotropy satisfying equation (1) does not guarantee that oscillation will occur simultaneously on two polarizations. This matter will be determined by the very complex questions of mode competition, coupling and so forth. As far as mode competition is concerned, initial expectations are that for a homogeneously broadened laser, mode competition will prevent simultaneous lasing on more than one mode (or polarization) while an inhomogeneously broadened laser might allow it. Indications of this effect are indeed observed in our experiments on the mostly collisionally broadened [7] HCN laser. However, inhomogeneities arising from differences in mode pattern prove sufficient to allow simultaneous oscillation for some transverse modes.

Another question, which is related to mode coupling, refers to the minimum ΔL necessary to establish independently oscillating modes. If the phase anisotropy is very small then independently oscillating modes will not exist because of the coupling between them. An approximate criterion is that if the effective cavity linewidth is $\Delta\nu_c$ then the modes will be independent if

$$\Delta L/L \gtrsim \Delta\nu_c/\nu \qquad (2).$$

If this is not satisfied then complicated mode coupling and possibly relaxation oscillations may occur. Evidence for such effects has been observed in the experiments.

Realisation

The laser on which the concept has been realised is an HCN waveguide laser of a type which has been described previously[5]. The cavity consists of a temperature controlled pyrex glass tube of length 3.2m and inner diameter 5.4cm, at the ends of which are plane reflectors. One of these reflectors is the output coupler consisting of a free standing copper electroformed mesh of rectangular symmetry with mesh constant 64 μm, and conducting strip width 15 μm, which has a power reflectivity of about 90% at 337 μm wavelength. The other reflector in the present experiments is a diffraction grating having 20 lines per mm and 26° 45' blaze angle, which independent measurements in a passive cavity have shown to introduce phase anisotropy corresponding to $\Delta L = 3.5 \pm 0.5$ μm.[6] The c.w. laser action is excited by an axial current of 1 to 1.4A in a flowing mixture of 6% Nitrogen 18% Methane 76% Helium at a total pressure of 1 to 1.5 torr.

Fig. 1 shows a laser resonator interferogram obtained by plotting the total power output, as registered on a Scientech 3600 power monitor (whose face is coated with ∿ 0.5 mm Nextel Velvet Black), as the grating reflector is slowly translated axially. The periodicity (168.3 μm) due to longitudinal mode spacing is clearly seen in the 337 μm wavelength radiation and different transverse modes are evident. These have been discussed and identified previously [5]. Significant power is also observed at 311 μm wavelength as indicated. The transverse modes in which we are mainly interested are the EH_{11} mode which is a linearly polarized gaussian-like mode and is the most powerful and most frequently used mode, and the mode identified as TE_{01}/EH_{21} which produces a total power only 20% less. It is on this latter mode that simultaneous oscillation at two frequencies has been observed.

The mode pattern of these modes has been examined by focussing the laser beam on to a fluorescent power probe; a wire grid polarizer is used to investigate the polarization. The EH_{11} mode, as expected, always shows as a single spot. Its polarization is found to be always a single linear polarization either approximately perpendicular or approximately parallel to the grating. As the cavity length is tuned through the mode a rapid 'flip' from one polarization to the other occurs. This flip shows as a cusp on the interferogram Fig. 1. Moreover there is hysteresis in this response; i.e. the flip occurs at a different point when the cavity is tuned in opposite directions. Behaviour of this sort has been observed previously[8] when phase anisotropy was accidentally introduced. With the present laser and grating no evidence of simultaneous independent oscillation on different EH_{11} polarizations has been observed. This is believed to be due to the effects of mode competition.

The mode patterns obtained for the TE_{01}/EH_{21} mode are illustrated, somewhat schematically, in Fig. 2a. With the cavity tuned to the peak of the mode the patterns 2(a)(i), (ii) and (iii) are obtained with no polarizer, polarizer wires vertical (passing E horizontal) and polarizer wires horizontal respectively. (The grating rulings are vertical.) With the cavity tuned off peak so that the cavity is shorter 2(a)(ii) is obtained with no polarizer or with vertical wires; no power is indicated with wires horizontal. Similarly if the cavity is tuned longer than peak the pattern 2(a) (iii) is obtained with no polarizer or horizontal wires and no power is indicated with wires vertical.

The electric field lines for the theoretical waveguide modes corresponding to the power measurements are illustrated in Fig. 2(b). (Mathematical treatment of these modes may be found in ref [9].) The linear anisotropy introduced by the grating would be expected to break the degeneracy by making the linearly polarized combinations $LP_{11} = TE_{01} + EH_{21}$ and $LP'_{11} = TE_{01} - EH_{21}$ the eigenmodes of the cavity. The measurements show that the cavity favours one or other depending upon which mode is nearest to the laser line centre; moreover with the cavity tuned to the peak power both these linear combinations are present.

In order to show that we are obtaining independent oscillation in the LP_{11} modes a fast pyroelectric detector, frequency-compensated to give flat video response to about 1 MHz, sampling only part of the beam pattern, is used to observe mode beating. With a polarizer horizontal or vertical very little modulation ($\lesssim$ 5%) is observed. However when the polarizer wires are at 45° the power on the detector is observed to be modulated, the degree of modulation is typically $\gtrsim$ 50% depending on cavity tuning and the exact part of the mode pattern being sampled.

The observation of beating with a 45° polarizer but not with vertical or horizontal, nor, in fact, without a polarizer is a clear indication that the laser is indeed oscillating independently at different frequencies on linearly polarized modes which, owing to their orthogonality, do not interfere with one another until the polarizations are mixed using an oblique polarizer. The mode pattern measurements show that these are the LP_{11} modes. Rotating the grating in the laser to set the rulings at an arbitrary angle it is found that the polarizations follow this rotation and align themselves approximately parallel and perpendicular to the rulings.

At any specific angle the cavity mirror alignment has to be optimised in order to obtain clear independent oscillation, perpendicular to the rulings, and approximately equal powers in the two modes. All the above results refer to such optimised alignment; under these conditions the modulation frequency is $\sim$ 900 kHz. This frequency corresponds to a difference in the effective cavity length of $\Delta L = L.\Delta\nu/\nu = 3.2\ \mu m$, consistent with the independently measured effect of the grating.

When the cavity alignment is not optimised, either no modulation or modulation frequency from about 200 kHz to about 1.2 MHz may be observed. At the lower frequencies the modulation is often distinctly non-sinusoidal and is present in the absence of a polarizer. Usually one mode of the cavity is dominant and the modulations appear to have the nature of relaxation oscillations in the amplitude of this mode. In one case where the modulation frequency was particularly low mode pattern observations showed the pattern 2(a)(i) without a polarizer and with a polarizer showed a two-lobed pattern with symmetry axis parallel to the polarization whatever the orientation of the polarizer. This indicates that the dominant mode is not a linearly polarized LP_{11} mode but rather is a TE_{01} mode.

It was found in retrospect that modulation up to almost 1 MHz frequency, having the relaxation oscillation character, can be obtained even with a plane mirror replacing the grating, by suitable cavity (mis-) alignment. Independent oscillation and true mode beating has not been observed without the grating.

With the grating in place, properly optimised alignment and independently oscillating modes, the 'instantaneous' bandwidth of the mode beating is found to be typically ∿ 5kHz FWHM. Slow drifts over periods of hours amount to some tens of kHz but arise because of slight changes in cavity length which can be adjusted periodically to compensate these drifts. This stability is significantly greater than that observed previously with two separate HCN lasers [10] (where 80 kHz bandwidth was observed) and arises presumably because the frequency modulating effects, determining the coherence of the laser, act nearly equally on each mode of the same cavity. A significant stability advantage is thus obtained by the present technique.

Discussion

A particularly simple technique has been demonstrated to provide laser output on two orthogonal polarizations at different frequencies. Because these are linear polarizations it is straightforward to separate them by a polarizer, to form, for example, the separate beams of an interferometer. Prior to their separation if their amplitudes are essentially equal we may regard the composite beam as oscillating in polarization at the beat frequency between the TE_{01} mode (= $LP_{11} + LP'_{11}$) and the EH_{21} mode (= $LP_{11} - LP'_{11}$). For this reason we refer to the effect as 'polarization modulation'.

Under some circumstances in the experiments, as has been described, the polarization modulation gives way to more complicated amplitude modulation having the character of relaxation oscillations. The fact that this occurs more often at lower frequencies points to the importance of the criterion for mode independence (eq. (2)). Taking the total cavity loss per double pass as 10% (which is probably optimistic) the cavity Q is about 1.2 x 10^6 and hence the cavity linewidth is about 700 kHz. Thus eq. (2) is only marginally satisfied at 900 kHz modulation frequency and not at lower frequencies. It is not surprising, therefore, that the experiments have shown complicated mode coupling effects.

It appears that the sensitivity of the modulation to cavity alignment should be understood by supposing that the mirror alignment can introduce additional anisotropies into the cavity, whether of phase or of loss (alignment may also affect the cavity Q.) These anisotropies need to be minimised in order to allow the grating to have its full effect. When a purely plane mirror is used, these anisotropies can themselves give rise to modulation but are insufficient to give true polarization modulation. If this interpretation is correct, then it seems that it may be easier to obtain independent mode oscillation by increasing the effective ΔL of the grating using a deeper ruling or by increasing the cavity Q. Experiments are planned to investigate these possibilities.

That no modulation could be observed in the EH_{11} mode is attributed to mode competition between the two polarizations which have identical power distributions. This interpretation is supported by the observation of hysteresis. An attempt was made to overcome this competition by decreasing the operating pressure, thus decreasing the dominance of collisional broadening over doppler broadening[7]. However no modulation was obtained at 0.3 torr pressure, where the power had fallen to about 2mW, even though the doppler line-width should then be about twice the collisional width. The situation is different for the LP_{11} modes because their power profiles in the cavity overlap only partially. Thus, even though the broadening mechanism is homogeneous, the presence of one mode still leaves a significant volume of the laser medium available to the other mode with sufficient gain to allow lasing to occur.

There seems every reason to suppose that the technique described should be successful for other discharge-excited submillimetre lasers such as the DCN (λ = 190/195 μm) and H_2O (λ = 118 μm) lasers. Indeed these may prove more amenable because of the increased importance of doppler broadening at their shorter wavelength. At still shorter wavelength it seems that nothing in principle should prevent the technique from working but in lasers where single mode operation is not automatic, obviously complications will arise.

The observed dependence of the polarization of optically pumped laser action upon the pump laser polarization may complicate the application of the technique to these submillimetre lasers but only experiments will show whether it can still be successful for them.

Acknowledgements

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References

1. e.g. Buchenauer C J and Jacobson A R, Rev. Sci. Instrum. 48 (1977) 769.
2. Asado O, Inoue A and Tsukishima T, Rev. Sci. Instrum. 51 (1980) 1308.
3. Veron D, Opt. Commun. 10 (1974) 95.
4. Wolfe S M, Button K J, Waldman J and Cohn D R, Applied Optics 15 (1976) 2645.
5. Belland P, Veron D and Whitbourn L B, J. Phys D, 8 (1975) 2113.
6. Hutchinson I H, submitted to Optics Communications.
7. Belland, P Ciura A I, Whitbourn L B, Opt. Commun. 11 (1974) 21.
8. Yamanaka M, Yoshinaga H and Kon S, Jap. J. Appl. Phys. 7 (1968) 250.
9. Marcatili F A J and Schmeltzer RA, Bell Sys. Tech. J. 43 (1964) 1783.
10. El-Hadj Tidjani M, Belland P and Veron D, Infrared Phys. 19 (1979) 677.

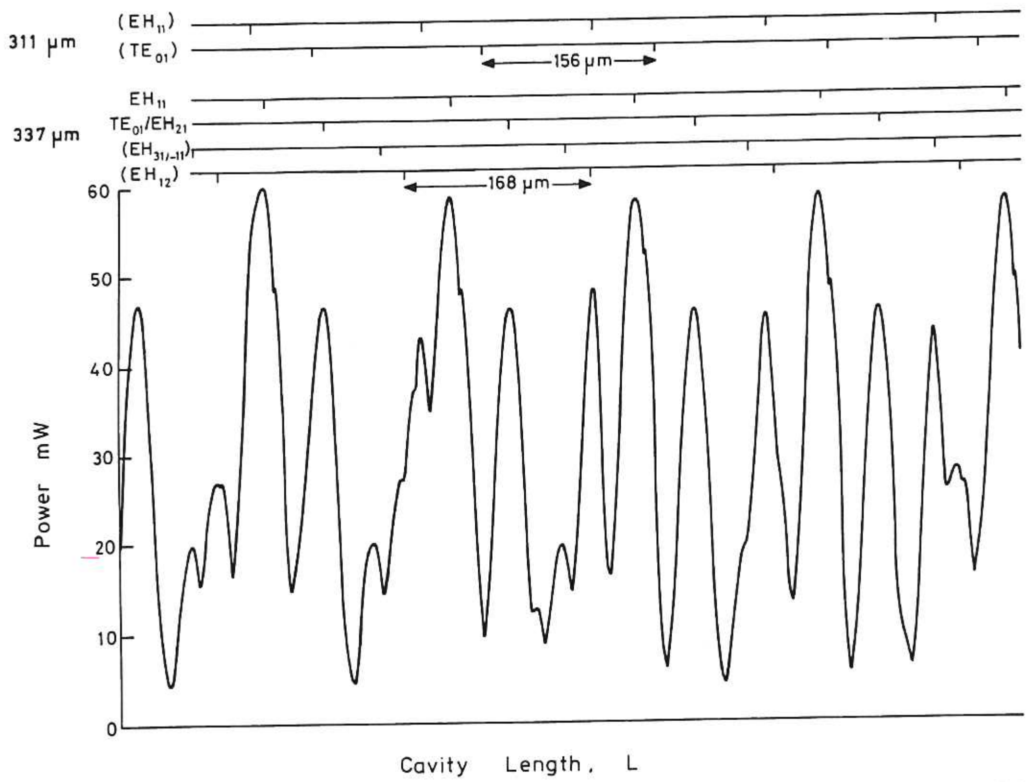

Fig.1 Laser Resonator Interferogram obtained by plotting total power versus cavity length. Positions of various transverse modes are indicated. Those identifications in brackets are tentative since for them mode pattern analysis was not performed.

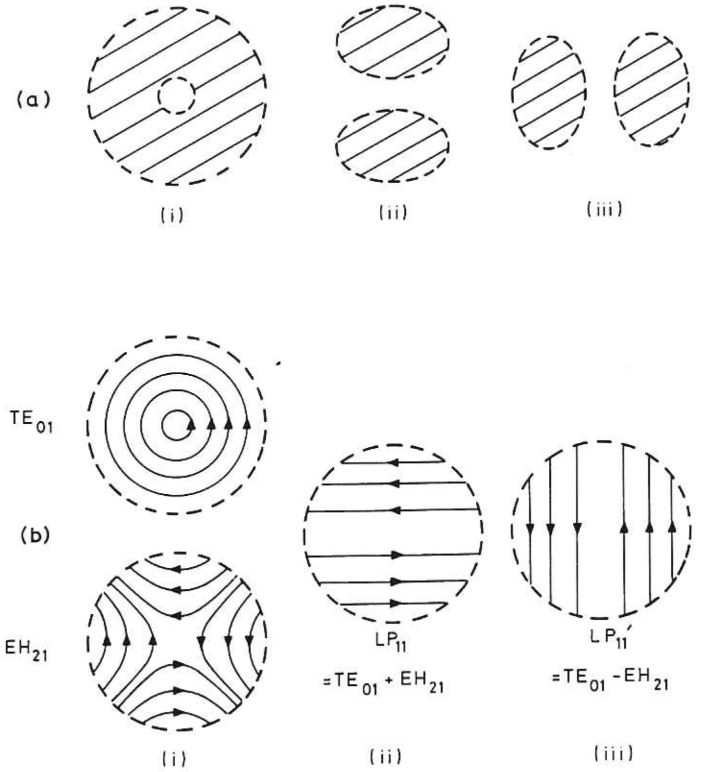

Fig.2 Mode pattern analysis of TE_{01}/EH_{21} mode. (a) Experimental power patterns: (i) Optimised; (ii) E-horizontal polarized or cavity shorter; (iii) E-vertical polarized or cavity longer. (b) Theoretical electric field patterns corresponding to the observations of (a).