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Laser Cavities with Increased Axial Mode Separation

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(Manuscript received October 28, 1965)

Single axial mode operation of gas lasers may be achieved either by reducing the mirror separation, L, until the mode separation, $c/2L$, is comparable to the oscillation line width, $\Delta\nu_a$, or by using mode suppression or filtering techniques.[1, 2, 3] When the line width exceeds ≈ 3 gc (as in an argon ion laser for example), L must be less than 5 cm for an unstabilized laser and less than 10 cm for a laser stabilized at line center.* Lasers of this length have several disadvantages, the most serious of which (in the case of ion lasers) results from the close proximity of the Brewster windows to the discharge. In the case of the 6328 Å He-Ne laser, restricting the laser tube length to a few centimeters limits the available single axial mode output power to about 1 mw.

This brief describes two additional mode suppression techniques which permit single axial mode operation with mirror separations much larger than $c/2\Delta\nu_a$.

In common with other techniques,[3] mode suppression is achieved by splitting the beam and using a three-mirror cavity;* however, the specific configurations described in this note are believed to be new and may possibly be advantageous in certain circumstances.

The first technique is most simply understood by referring to Fig.

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* The mode competition effects reported by Rigrod and Bridges (Electron Device Research Conference, University of Illinois, Urbana, June, 1965) for ion lasers may permit some increase of these lengths.

* It has been pointed out by E. I. Gordon and J. E. Geusic that all mode suppressors using a beam splitter and three mirrors are probably members of the same class of devices characterized by the microwave magic tee with two shorted arms.

1(a) which illustrates one of several possible versions. In Fig. 1(a), G is a conventional Brewster window gas laser; M_1, M_2, and M_3 are spherical mirrors; and C is a birefringent crystal such as calcite with antireflection coated faces. The crystal is oriented so that plane polarized light defined by the Brewster window is split by the crystal into two parallel, orthogonally polarized beams (not necessarily of equal intensity) displaced from each other by a small distance, d, determined by the length of the crystal. The radius of M_3 is chosen to match the spot size and curvature of the beam formed by mirrors M_1 and M_2.

For light of the correct polarization and for a given transverse mode, the cavity has low loss only for those frequencies for which the optical path length L_{13} is an integral number of half wavelengths longer than L_{12}.* By proper adjustment of L_{23}, the low-loss modes for the "bi-cavity" may be spaced sufficiently far apart so that only one mode appears within the oscillation linewidth. This mode may be interpreted as a coincidence between axial modes of the cavities formed by mirrors $M_1 - M_2$ and $M_1 - M_3$ separately as indicated in Fig. 1(b). The difference in mode spacing

$$\Delta\nu_m = \frac{c}{2}\left(\frac{1}{L_{12}} - \frac{1}{L_{13}}\right)$$

must be large enough so that oscillation at modes adjacent to a coincidence does not occur† and small enough so that only one (or at most two) coincidences occur within the oscillation linewidth. The separation between coincidences, $\Delta\nu_c$, is given by $c/2(L_{13} - L_{12})$. If, for example, $L_{12} = 100$ cm, $L_{13} = 115$ cm, $\Delta\nu_m = 19.5$ mc and $\Delta\nu_c = 1000$ mc.

Numerous variations of the same general technique exist. Since calcite crystals capable of yielding beam displacements larger than 1–2 mm are difficult to obtain, the beam splitter may conveniently be a Wollaston or Rochon prism which provides a few degrees of angular separation, as illustrated in Fig. 2(a). In order to achieve higher single mode powers, the arrangement shown in Fig. 2(b) is advantageous since the tube length can be approximately doubled with no increase in over-all cavity length.

Because of the large difference in refractive index for e and o rays

* Light from M_2 and M_3 for which $(L_{13} - L_{12})$ is not an integral number of half wavelengths is elliptically polarized when recombined by the calcite prism and one component is partially reflected out of the cavity by the Brewster window.

† It can be shown that the cavity loss at modes adjacent to a coincidence increases with $(L_{13} - L_{12})$; consequently, the discrimination against adjacent modes increases with $\Delta\nu_m$.

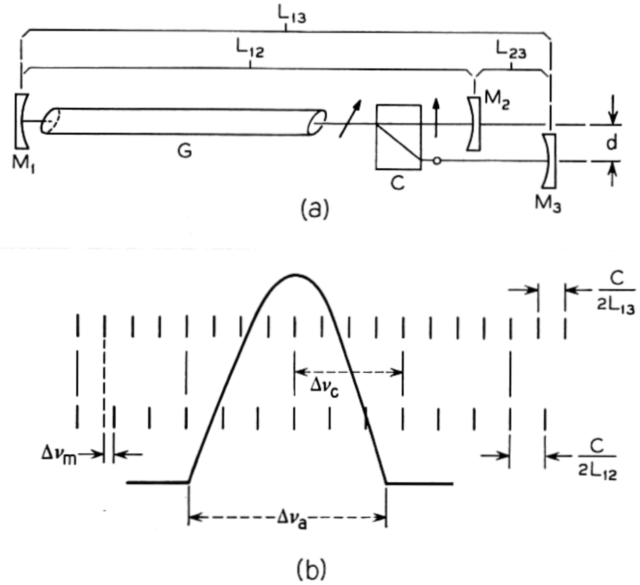

Fig. 1 — (a) Mode suppression technique using calcite rhomb beam splitter. (b) Coincidences between modes of the cavity shown in 1(a).

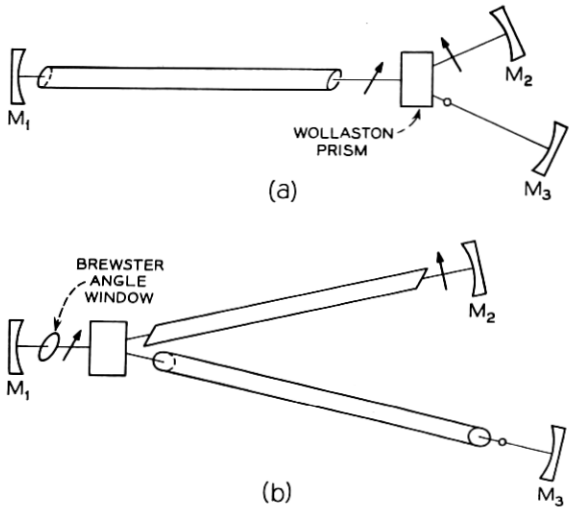

Fig. 2 — (a) Mode suppression technique using a Wollaston prism beam splitter. (b) Technique for increasing output power with no increase in over-all length.

in calcite, it is impossible to eliminate reflection for both rays simultaneously by antireflection coating unless birefringent coatings can be developed. This index difference is much smaller for crystal quartz, consequently the reflection coefficient can be made low for both rays. The deviation angle is reduced to about 2° which is still sufficiently larger than the diffraction angle of the beam in most gas lasers to allow complete separation of the beam in a few centimeters distance.

The feasibility of the bicavity approach has been demonstrated using a calcite Wollaston prism in conjunction with 60 cm long 6328 Å gas laser as illustrated in Fig. 2(a). In order to reduce reflection losses, glass windows having $\lambda/4$ cryolite coatings on one surface were oiled to each prism face. All three highly-reflecting (>99.6%) mirrors had a radius of curvature of 2 meters. L_{12} and L_{13} were approximately 122 cm and 142 cm, respectively, giving a difference in mode spacing $\Delta\nu_m$ of 17.3 mc and a separation between coincidences $\Delta\nu_c = 750$ mc. Since the 6328 Å oscillation linewidth is $\approx$1500 mc at most two axial modes can oscillate in this arrangement. The mode structure of the bicavity laser was examined with a plane parallel Fabry Perot interferometer having a free spectral range of 3 gc. Provided an aperture was used in the laser cavity to discriminate against all but the lowest order transverse mode, at most two axial modes with a separation estimated at $\approx$750 mc were observed to oscillate. Single-mode operation was obtained intermittently as one of the bicavity modes passed through line center.

Because of poor index matching, most of the output power appeared as reflections from the Wollaston prism with only a small amount ($\approx$2 mw) being transmitted through the high-reflectivity mirrors. Reducing the reflection loss by using a quartz prism and low-loss coating should permit single-mode powers in excess of that available in a single axial mode from a multimode laser of the same length, as pointed out by Smith.[3]

A second technique, simpler than the first, but more restricted in application, makes use of the symmetry of the TEM_{01} mode. The line of symmetry of this mode (and other odd symmetric modes) is a region of zero field, consequently, splitting the mirror along this line should not appreciably increase the loss for this mode. One may form a bicavity configuration by placing each half of the split mirror at different distances from the common mirror as shown in Fig. 3(a). In order to minimize losses, the spot size at the mirror should be made as large as the tube bore permits by using a nearly concentric cavity.

The split mirror approach has been demonstrated experimentally,

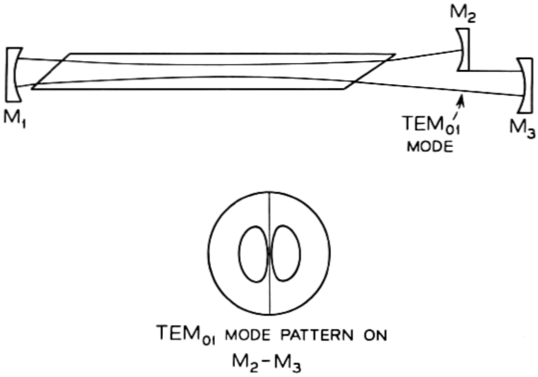

Fig. 3 — Mode suppression technique suitable for TEM_{01} mode.

using for this purpose 1 meter radius mirrors spaced approximately 176 and 183 cm apart. Care was taken to produce a sharp edge at the front surface of the nearest split mirror (M_2 in Fig. 3(a)) to minimize scattering losses. The TEM_{01} mode was selected by using an aperture at the common mirror. An interferometer was used to verify single axial mode operation as in the previous experiment.

Since each half of the split mirror has to be mounted separately, some difficulty was experienced in aligning the cavity to produce the desired mode. However, once the mirrors were oriented correctly, the mode was found to be quite stable.

Because of the increased diffraction angle, the TEM_{01} mode is not the best choice for beam propagation. Unfortunately, there seems to be no way of applying the split mirror approach to the TEM_{00} mode, but it may be possible to suppress axial modes of the "donut" TEM_{01} circular mode.

The author is grateful to his colleagues for interesting and constructive discussions.

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