EFFICIENT SINGLE MODE OPERATION OF A CW RING DYE LASER WITH A MACH-ZEHNDER INTERFEROMETER

J.C. BERGQUIST and Lee BURKINS *

Time and Frequency Division, National Bureau of Standards, Boulder, CO 80303, USA

Received 30 January 1984

Stable single mode operation of a ring dye laser is obtained with the combination of a Mach-Zehnder interferometer (MZI), three plate birefringent filter, a single thin etalon and a unidirectional diode. The MZI eliminates the fractional insertion loss due to beam walk-off and distortion which an intracavity etalon must introduce in order to select single frequency operation. We experimentally demonstrate the low insertion loss, single mode stability and frequency tuning of a ring dye laser using a specially designed, compact MZI. Finally, we propose MZIs with no coatings, which should permit extremely low loss broadband operation.

1. Introduction

To achieve and control single frequency operation of a high power cw ring dye laser, more than one intracavity frequency selective element is required.

While a unidirectional ring laser very often runs single mode with a birefringent filter and no etalons, it is not mode stable. In our experience, a quiet environment, a good circulation system, and an uncoated, one millimeter thick etalon provides stable single frequency operation for 5–20 minute periods. Superior mode control performance is possible with the addition of a second, air spaced, thick (~10 mm) etalon. However, this highly stable mode control comes at the expense of output power due to the insertion losses of the etalons. Etalons can never give zero insertion loss, because they must be used at a small angle to the normal in order to select single frequency operation [1]. The resulting etalon walk-off losses, large number of optical surfaces and thermal absorption effects combine to give a fractional insertion loss per pass that is never less than, and frequently exceeds, 1.5%. It is this loss which led us to seek alternative methods for controllable single frequency operation in ring dye lasers.

* Present address: Hilo, Hawaii.

Recently, Pinard et al. [2,3] reported an efficient cw single mode standing wave laser using a double or triple Michelson interferometer system (MIS). In their laser, the plane mirror output coupler was replaced with the MIS. The MIS selected single mode operation of the laser and served as a partially transmitting retroreflector (it could also work as a highly reflecting retroreflector). In a ring laser, retroreflection, or feedback, is undesired, thereby eliminating the MIS from practical consideration. However, a variation of the Michelson interferometer, the Mach-Zehnder interferometer [4], has the attractive features of the MIS as a frequency selective element but with no feedback. In this paper we discuss the operation of a single mode ring dye laser using a Mach-Zehnder interferometer.

2. Theoretical considerations

The Mach-Zehnder interferometer (MZI) (fig. 1) consists of two beam splitters and two highly reflecting mirrors, and belongs to that general class of interferometers which depends on division of amplitude to derive interference. The two beams obtained by amplitude division are sent in different directions, reflected, and recombined to form interference fringes. In the

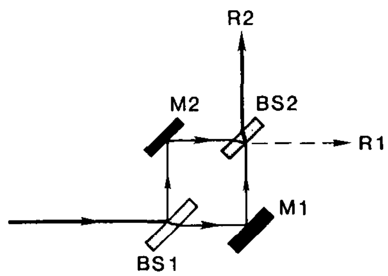

Fig. 1. Mach-Zehnder Interferometer (MZI).

MZI there is no light retroreflected in the direction of the incident beam. Furthermore, if the reflectance of both beam splitters is identical, then the transmitted beam, R1, exhibits total destructive and constructive interference as the path length difference of the split beams is varied. Thus, the MZI may be adjusted to give zero intensity for R1, but, in general, it may not be adjusted to null the intensity of the transmitted beam, R2. To see this let us represent the amplitude reflection coefficient of the beam splitters as r and the transmission coefficient as $t \approx (1 - r)$. R1 is made up of a beam which is first reflected, then transmitted by the beam splitters and a beam which is first transmitted, then reflected by the beam splitters. Since $rt = tr$, R1 always exhibits 100% contrast independent of the value of r. However, R2 consists of a beam which is twice reflected (rr) and a second beam which is twice transmitted (tt). In general R2 will not show total contrast since $rr \neq tt$ except for the special case that r is precisely equal to t (this is the reason that the MIS will generally have feedback). Thus, for most efficient operation of the laser, R2 is chosen to be intracavity and R1 is selected to be the auxiliary beam. By the above arguments, R1 is expected to have zero amplitude when the MZI is correctly aligned and the laser is oscillating.

3. Experimental description

Fig. 2, shows the basic elements of the ring laser with our compact version of the Mach-Zehnder interferometer illustrated in the accompanying inset. One piece of optical quality, plane parallel, synthetic fused silica, 25.4 mm round by 9.5 mm thick, is used for both beam splitters and one high reflector. The first surface is coated to be ~50% reflecting at 45° angle of incidence and the second surface coated to be highly reflecting. This eliminates one surface and the need for either an anti-reflection coating or a Brewster angle cut. Additionally, since there is but one beam splitting surface, the reflectance can be made essentially identical everywhere. This eliminates the need to match beam splitters and better insures

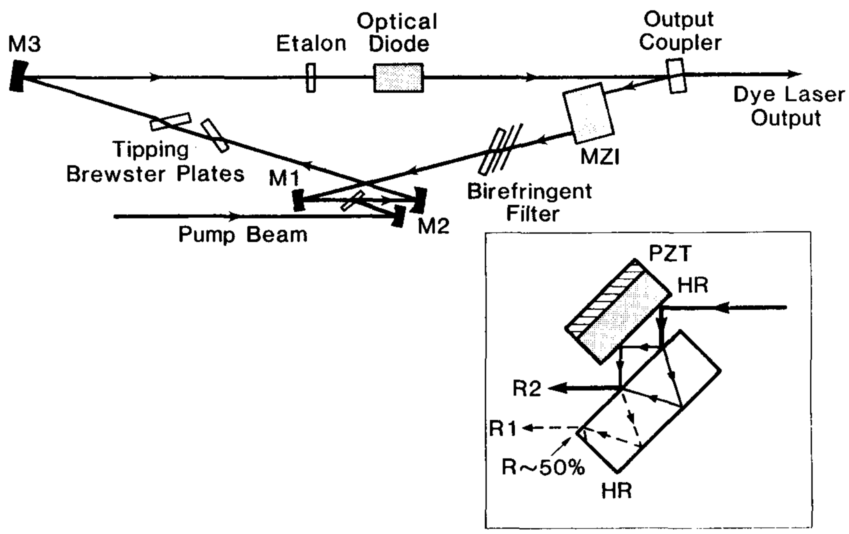

Fig. 2. Ring dye laser with intracavity MZI to select single mode operation. Inset shows the details of the compact MZI.

that the auxiliary beam, R1, which escapes from the laser has nearly zero intensity.

Ideally, then, a correctly aligned and properly oriented MZI should have no insertion loss. (The MZI must be oriented so that the incident light beam is strictly p polarized or strictly s polarized. Otherwise, the difference in phase for total internal reflection between p polarization and s polarization leads to elliptical polarization, imperfect interference and a higher loss). Practically there are some scattering and absorption losses in the coatings (the absorption and scattering losses in the synthetic fused silica substrate are small in comparison). Also there can be some thermal lensing effects in the beam splitter and in the coatings at high powers. Finally any beam wavefront curvature can lead to imperfect superposition of the recombined beams (which have traveled different optical pathlengths) leading to incomplete destructive interference. These types of losses, all of which are also encountered with coated intracavity etalons, can be made very small – certainly on the order of 0.7% per pass or less. In the final section we propose two examples of MZI's which eliminate all coatings and their attendant losses.

The MZI is either prealigned by using a HeNe laser external to the dye laser, or simply by using the dye laser fluorescence spots. The light beams, or spots, in the direction of the transmitted beam, R2, in fig. 2 are first brought into coincidence both in the near field and in the far field. The laser cavity mirrors are then adjusted for lasing. When the laser is operating, a final iteration of the MZI alignment is done for optimum power. It is best to do this final optimization without other intracavity frequency selective elements. We found that a very sensitive way to do the final optimization was to make concentric and to minimize the number of interference fringes in the beam R1 (see inset, fig. 2).

The free spectral range (FSR) of our compact MZI is given by

$$\mathrm{FSR} = \frac{cn\cos\theta}{2d(n^2-1)},$$

where c is the velocity of light, n is the index of refraction, θ is the angle of refraction, and d is the thickness of the plane parallel splitting glass. Our choice of angle of incidence (45°) index of refraction ($n = 1.46$), and thickness ($d = 9.5$ mm) gives a free spectral range of 17.8 GHz. The peak of the MZI's transmission is slaved to follow the selected laser mode by means of a servo system which controls the excursion of a PZT attached to the highly reflecting mirror. A 3 kHz signal modulates the position of this mirror which causes a corresponding modulation of the laser's output power due to the impressed mismatch of laser cavity mode with MZI mode. Phase sensitive detection of the laser's power gives an error signal which is integrated and fed back to the PZT to center the MZI to the peak of the laser's output power. The gain of the servo system is adjusted so that short duration interruptions to the laser oscillation (e.g., bubbles in the jet) do not cause any mode hops. As pointed out by Pinard et al. [2], laser frequency modulation does occur as a result of the modulation of the MZI but this is not unique to the Mach-Zehnder or Michelson interferometers. It is also present if the optical spacing of a Fabry-Perot etalon is modulated. Changing the thickness of an etalon or the length of one arm of the MZI modifies the phase of the transmitted beam, thereby changing the effective length of the laser and its frequency. The laser frequency modulation amplitude is small and can be eliminated by electronic servo control, a feed forward signal, or both.

4. Results

The ring dye laser with the dye Rhodamine 6G was first made to oscillate with a 90% reflecting output coupler, a unidirectional diode, a three plate birefringent filter and a 1 mm thick uncoated etalon (we have also tried a 0.45 mm thick, 22% reflection coated etalon with similar results). The laser alignment was optimized to give maximum output power with a 4 W all lines argon ion pump laser. This resulted in a power of approximately 820 mW. The MZI was then inserted into the laser cavity and the MZI and laser were optimized for greatest output power. The maximum dye laser power of ~735 mW corresponded to a 10% drop in output power. A determination of the other intracavity laser losses gives a fractional insertion loss per pass of approximately 0.7–0.9% for the MZI. By measuring the power in R1, after the beam splitting surface, we determined what fraction of the insertion loss was due to scattering and absorption as opposed to loss due to imperfect destructive interference. The curvature of the wavefronts at the intracavity insertion point of the MZI led to a measured imperfect destructive interference loss of ~0.45%. Thus the remaining loss is associated with the scattering and absorption in the coatings and is not unreasonable.

To determine the ability of the MZI to lock and remain locked on a single laser mode, two experiments were performed. In both tests the output of the laser was single passed through an $^{127}I_2$ cell. The fluorescence which resulted from the coincidence of laser frequency with an arbitrary molecular line was monitored with a 1P28 photomultiplier tube. In the first experiment the laser was tuned to the half power point of the iodine line and the MZI was locked as earlier described. Otherwise the laser was left free running (free running linewidth ~1 MHz for 1 s averaging times). Fig. 3a is a strip chart recording of the monitored fluorescence signal. Stable, single mode operation of the laser typically exceeded several hours if the center frequency of the thin etalon was occasionally realigned to match the laser's frequency to compensate for thermal drifts. In fig. 3b the frequency of the laser was swept up and down by approximately 8 GHz (limited by the untuned thin etalon). A feedforward signal was applied to the MZI to minimize the requirements of the servo system to maintain lock. Again, the laser remained mode stable, the MZI demonstrating no difficulty in locking to and tracking the sweeping laser. It should be straightforward to tune the laser by as much as 40 GHz with this system and a frequency tuned thin etalon (in this case the frequency sweep would be limited by the untuned birefringent filter).

5. Low loss, broadband MZI

Two examples of MZI's with no coatings and suitable for single frequency ring dye laser operation are shown in figs. 4 and 5. Both are constructed of high optical quality, UV transmitting, synthetic fused silica, which averages about two orders of magnitude

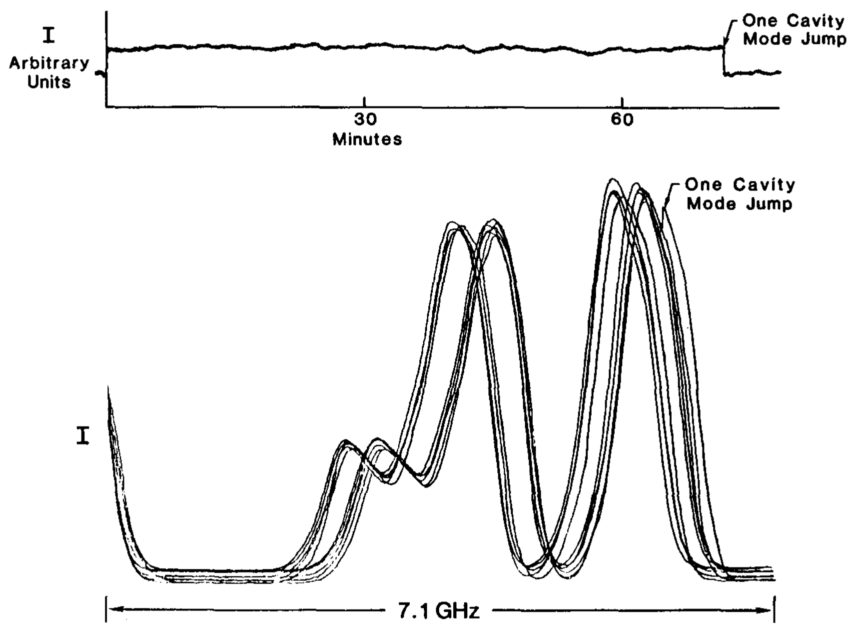

Fig. 3. Fluorescence signals from an arbitrary $^{127}I_2$ line excited by the single frequency ring dye laser. In the upper trace, the laser was frequency tuned to the side of the iodine line and the MZI was servo locked to match the laser's frequency. The laser was left free running. In the lower trace, the MZI is servo locked again to match the laser's frequency, but now the laser is frequency swept by ~7.1 GHz. In both traces a deliberate single cavity mode jump is indicated.

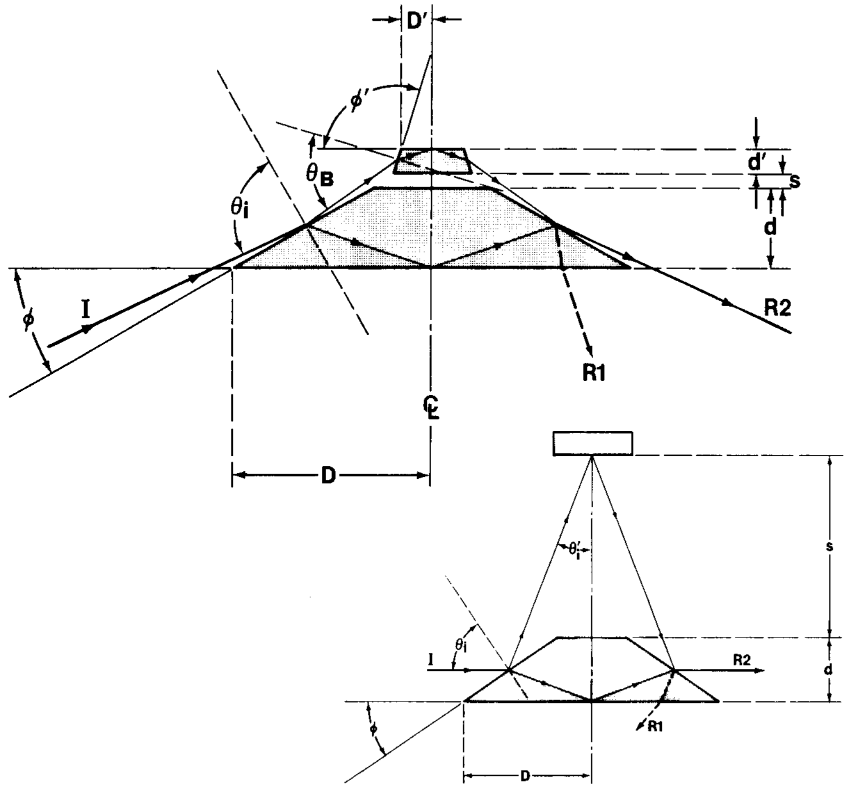

Fig. 4. An example of a broadband low loss, uncoated MZI. Inset shows a low loss, partially coated MZI suitable for s polarization. See text for discussion. A possible choice for the dimensions, angles and FSR for each of the MZIs follows: $\theta_i = 85°$, $\theta'_B = 55.6°$, $\phi = 29.6°$, $\phi' = 111°$, $D = 42$ mm, $D' = 9.5$ mm, $d = 17$ mm, $d' = 5$ mm, $s = 1.7$ mm and FSR = 42 GHz; for inset, $\theta_i = 55.6°$, $\theta'_B = 21.2°$, $\phi = 34.4°$, $D = 19$ mm, $d = 9.4$ mm, $s = 26.6$ mm and FSR = 10.2 GHz.

less absorption loss than the best optical glass across the visible spectrum [5]. The absence of any coatings and the low bulk absorption coefficient combine to make these MZIs highly efficient, totally broadband, intracavity frequency selective devices for any dye in the visible and near IR. The insertion loss of these two MZIs will be dominated by surface polish, surface figure, and mismatch of wavefront curvature for the recombined beams. Thus, a fractional insertion loss per pass below (and, perhaps substantially below) 0.4% is realistic. This is particularly valuable to the operation of ring lasers with high threshold dyes.

In fig. 4, the larger fused silica substrate acts as both beam splitters and one high reflector. The second, smaller substrate serves as the other high reflector. The laser beam, I, incident on the larger substrate, is partially transmitted at the first surface. The transmitted component suffers one total internal reflection and then recombines with the reflected component to produce the interference beams R1 and R2. The first surface reflected beam enters the second substrate at Brewster's angle, suffers total internal reflection, exits, again at Brewster's angle, before recombining with the first surface transmitted beam. For lowest loss, this MZI must be oriented such that the incident beam on all surfaces is p polarized. The angle of incidence, θ_i, for the beam splitting surface is chosen to give sufficient contrast in the beam R2 for good mode selectivity and stable single frequency operation balanced against the ease and cost of cutting and polishing large area optical components (although the beam R1 displays 100% contrast independent of the common reflectance of the beam splitters, this does not determine the strength of the MZI). For $\theta_i = 85°$, the power reflection coefficient is 50% and R2 exhibits 100% contrast; for $\theta_i = 77°$, the power reflection coefficient is 15% and R2 exhibits 50% contrast (i.e., a reduction of only 2 in the ability of the MZI to reject the next adjacent mode). Frequency tuning of the MZI is accomplished by varying the relative spacing, *s*, between the substrates. The plane containing the center line and lying normal to the surface of the drawing is the plane of symmetry for fig. 4.

We note that, with only a small increase in the fractional insertion loss (<0.2%), the MZI of fig. 4 may be greatly simplified by the substitution of a highly reflecting mirror for the smaller substrate (see inset). This mirror could be changed when the other laser mirrors are changed to accommodate a different wavelength. The remaining part of the MZI would remain totally broadband and extremely low loss. Since the Brewster angled substrate is eliminated, the MZI may be made to work with s polarization. The insert of fig. 4 shows a particular attractive scheme which uses s polarization but does not deviate the incident beam.

The second example of a low loss broadband MZI is shown in fig. 4b. This double-substrate system not only acts as the MZI but also as the thin etalon. The laser beam, *I*, incident on the first surface of the first substrate is partially reflected and partially transmitted. The transmitted component suffers a total internal reflection and then exists the first substrate nearly normal to the exit plane. After traveling across a small, plane parallel, air space between the two substrates, it enters the second substrate. The air gap constitutes an uncoated, tunable thin etalon. In the second substrate, the transmitted component suffers a second total internal reflection, and then recombines with the reflected component to give the interference beams R1 and R2. The partially reflected component travels only an air path from the first substrate beam splitting surface to the second substrate recombination surface (note that for each of the amplitude split beams there must either be an even number of reflections or an odd number of reflections, but the number of reflections need not be the same for the two beams). Frequency tuning of the MZI can be done independently of the thin etalon by sliding one substrate up and down with respect to the other in a plane parallel to the plane of symmetry. The plane of symmetry lies midway between the two identical substrates and is normal to the surface of the drawing. Similarly, the thin etalon can be tuned independently by varying the spacing, *s*, between the substrates along an axis normal to the plane of symmetry.

Other than a small change in the value of the reflectance, the operation of the MZI in fig. 4 remains unaltered by the change in the index of refraction with wavelength. The angle of refraction at the entrance face is equal to the angle of incidence at the exit face (true for both substrates), independent of the index of refraction. Therefore, as a function of wavelength, there is no angle dispersion in the two beams which recombine to produce the interference beams R1 and R2. This is not true for the MZI of fig. 5. With a change in wavelength the corresponding change in the index of refraction gives rise to an angle dispersion in the beams which recombine to give R1 and R2. The angle dispersion can be exactly compensated by a small rotation of the MZI about an axis normal to the plane of incidence. However, this will increase the fractional insertion loss due to the increased beam walk off loss of the thin etalon.

In the caption to figs. 4 and 5, we list a possible choice for the dimensions, angles and free spectral range for each of the MZIs. For a constant effective aperture, smaller angles of incidence require smaller optical components but only at a loss of contrast and, hence, ability of the MZI to select and maintain single mode operation. The reflectance drops quickly as the angle of incidence decreases from 90°, although the reflectance for s polarized light drops less quickly than that for p polarized light (still giving 15% reflection and 50% contrast at Brewster's angle of approx-

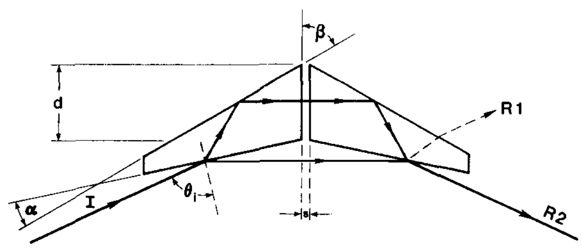

Fig. 5. A second example of a broadband low loss, uncoated MZI with an internal air spaced thin etalon. See text for discussion. A possible choice for the dimensions, angles and FSR follows: $\theta_i = 77.7°$, $\alpha = 17.8°$, $\beta = 59.8°$, $d = 8.8$ mm, $s = 1.0$ mm, FSR = 13.4 GHz.

imately 56°). Perhaps, then, the simplicity of the MZI in the inset of fig. 4, which does not deviate the incident beam nor require any extra mirrors, combined with the reduced substrate dimensions, makes it the overall best choice in spite of the one coating loss. We plan to study ring dye laser operation with this MZI in the near future.

Acknowledgement

It is a pleasure to thank our colleagues, R.E. Drullinger and C.R. Pollock for their many useful comments. We gratefully acknowledge the support of the United States Air Force Office of Scientific Research and the Office of Naval Research.

References

[1] W.R. Leeb, Appl. Phys. 6 (1975) 267.
[2] M. Pinard, C.G. Aminoff and F. Laloë, Appl. Phys. 15 (1978) 371.
[3] M. Pinard, M. Leduc, G. Frénec, C.G. Aminoff and F. Laloë, Appl. Phys. 19 (1979) 399.
[4] See for example, F.A. Jenkins and H.E. White, Fundamental of optics (McGraw-Hill, Inc., New York, 1957) p. 257-58.
[5] See for example, Optics Guide 2 (Melles Griot, Irvine, California, 1982) p. 65.