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A prism reflector of anti-resonant ring configuration

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Two identical prisms are combined to form an anti-resonant ring reflector, giving total reflection without the use of coatings or roof edges. When used as the total reflector in a Q-switched NdYAG laser this device has shown a damage threshold twice that of a multilayer reflector.

The concept of the anti-resonant ring interferometer first gained prominence in a laser context when, in 1972, Siegman [1] indicated a number of its potential uses. An early demonstration of its use was in cavity dumping [2]. More recently [3, 4] it has excited interest as a means of providing a colliding-pulse configuration, which has been shown to possess advantages in passive mode-locking [5]. It is interesting to note that McGeoch, in 1970 [6], had used a prism reflector device based on the anti-resonant ring principle and had, in addition, exploited its colliding-pulse configuration in a mode-locked ruby laser. The primary motivation behind McGeoch's prism reflector design was the need to overcome damage limitations imposed by multilayer dielectric reflectors while avoiding also the disadvantages of internal reflection at a prism roof-edge. Subsequent improvements in the power handling capability of multilayer coatings then diminished the attractions of this prism reflector. Recently, however, Vanherzeele [7] has drawn attention to the possibility of using the McGeoch prism reflector to provide a compact device suitable for a colliding pulse mode-locking set-up. Our own re-examination of this prism reflector has been motivated in part by a renewed interest in reflectors of high damage threshold since the output power capability of a Q-switched TEM$_{00}$ mode NdYAG laser employing a telescopic resonator [8–10] is determined by damage to the reflector in the contracted beam.

We describe here the design and performance of a modified version of the McGeoch reflector. We have confirmed by measurement that it has a damage threshold twice that of a multilayer reflector when used as the total reflector of a Q-switched NdYAG laser. An important difference from the McGeoch design is that the beam splitting surface does not involve frustrated total internal reflection (FTIR) to achieve the required 50% reflectivity and the device can therefore be realized with less exacting requirements on the prism spacing*. In fact, this increased design freedom suggests other possibilities, such as controllably varying the prism spacing and thus achieving a reflectivity adjustable between zero and 100% for any wavelength within the transmission range of the prism material.

The basic arrangement of an anti-resonant ring is shown in Fig. 1. The beam splitter divides the incident beam into two counter-propagating beams which then recombine at the beam splitter. The transmitted beam is the superposition of a contribution from the clockwise circulating beam, which undergoes two reflections at the beam splitter (one from each side) and a contribution from the anti-clockwise beam which undergoes two transmissions through the beam splitter. These two contributions to the transmitted beam are therefore in exact antiphase, regardless of the angle of incidence at the beam splitter. Thus if the beam splitter has 50% power reflectivity the counter-

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*We note that Vanherzeele has also chosen, like McGeoch, the more exacting option of using FTIR at the beam splitter interface.

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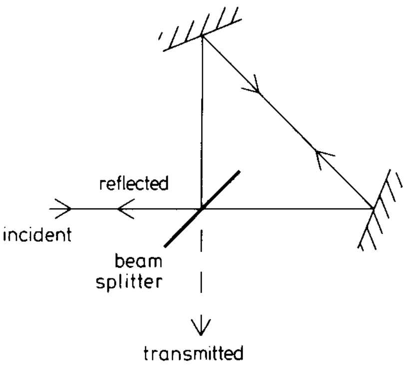

Figure 1 The anti-resonant ring.

propagating beams are of equal intensity, the transmitted beam is therefore of zero intensity, and the reflected beam carries all the incident power. The arrangement in Fig. 1 can be realized in a number of ways, using two identical prisms. Fig. 2a shows the design we have tested. The required 50% reflectivity at the beam splitter (which now consists of the two adjacent prism faces) can be achieved for a range of angles of incidence at the beam splitter. In fact the two faces act as a Fabry–Perot interferometer and given the angle of incidence one simply has to choose the appropriate spacing d (or vice versa) to achieve 50% reflectivity. It is also possible to use angles of incidence greater than the critical angle and thus involve FTIR. This is not necessary however since 50% reflectivity can be obtained from uncoated prism faces, for angles less than the critical angle, and the antiphase property remaining the same as for FTIR. The advantage of working at less than the critical angle is that the prism spacing can be much larger (and hence achieved more conveniently) than for FTIR. In fact one can exploit the interference behaviour of the beam splitter faces, whereby the reflectivity is the same for values of d differing by an integral multiple of $\lambda/2 \cos\theta$ where θ is the angle of incidence in the air gap between the prism. We have also used this interference behaviour to arrange for zero reflectivity where the beams cross the beam splitter at normal incidence, choosing $d = \lambda = 1.06\,\mu\text{m}$, this being the operating wavelength of the laser at which the 100% reflectivity was devised. Having chosen d, the angle of incidence at the interface was determined (θ = 40.56°, the prism material being BK7 glass) and this in turn fixes α (6.98°, since a Brewster angle input was required) and β (110.28°).

The construction of this device calls for two identical prisms with all the reflecting faces arranged perpendicular to one plane. A single prism was first made (Fig. 2b) with the angles α, β as specified (tolerance ±1 min) and the bases ABCD, A′B′C′D′ perpendicular to the reflecting faces (tolerance ±2 sec on perpendicularity). This prism was then cut in half (along plane A″B″C″D″) and the bases ABCD, A′B′C′D′ placed in contact with the surface of an optical flat. To provide the correct prism spacing two thin strips of dielectric were evaporated onto the longest face of one prism (Fig. 2b) leaving the centre of the face clear. The entire assembly was then mounted in a conventional mirror mount having micrometer angular adjustments

The following tests were carried out to assess the performance of the reflector. First a visual observation was made of any fringes resulting from

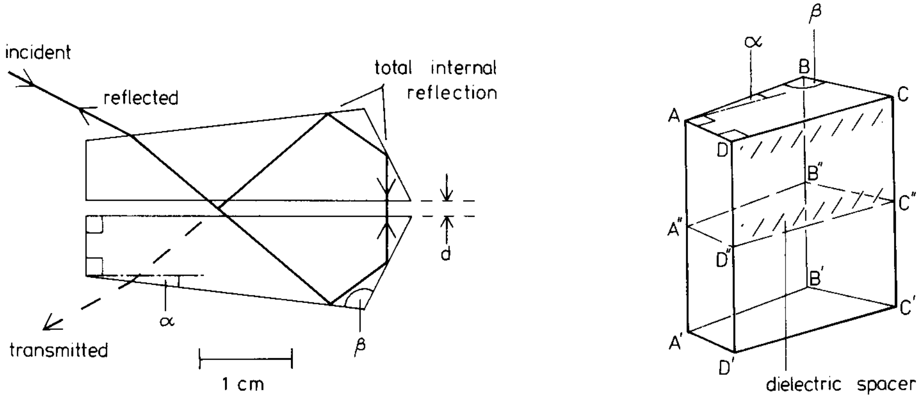

Figure 2 (a) A scale drawing of the actual reflector which was constructed and tested; α = 6.98°, β = 110.28°, and d = 1.06 μm (nominally). (b) Method of fabricating the identical prisms for the reflector.

imperfect parallelism between the beam splitter faces and between the prism bases ABCD, A′B′C′D′ and the optical flat. For the beam splitter faces excellent parallelism was easily achieved with no fringes visible across the face (of sides DC = 35.5 mm, CC″ = 15.0 mm). The parallelism between the prism bases and the optical flat to which they were contacted was found to be less good and it was estimated that the two prism bases were as much as 5 sec out of parallelism. The origin of this lack of parallelism is not certain, although it is probably due to imperfect contact with the optical flat. However, it does not appear to have significantly degraded the reflector performance. The reflectivity was measured in two ways: (1) using for the incident beam the horizontally polarized TEM_{00} output from a NdYAG laser, and (2) using the device as one of the reflectors of a NdYAG laser. In the first method the prism was aligned for retroreflection and a beam splitter was used for monitoring the incident and reflected beams. This measurement was of limited accuracy, but confirmed that the reflected beam had an intensity of $> 95\%$ of the incident beam. A small output was observed in the direction of the transmitted beam, $\sim 1\%$ of the incident beam and this was found to consist mostly of light polarized perpendicular to the plane of polarization of the incident light. These results suggest the presence of some strain-induced birefringence. In the second more accurate method, a measurement of threshold was made with the prism used as one reflector of a NdYAG laser, and a comparison with the threshold for a multilayer total reflector indicated a reflectivity of $> 99\%$.

To check the power handling capability of this reflector tests were made with a Q-switched NdYAG laser having a telescopic resonator configuration, the reflector being in the contracted beam [9]. The resonator dimensions differed somewhat from those of [9]; the rod diameter was 6 mm, the beam expansion telescope had x 3 magnification and the spacing between the telescope and the prism reflector was 0.35 m. The laser output was taken from the expanded beam end of the resonator, using a single uncoated glass surface as the output. Under these conditions it was found that a multilayer dielectric mirror used as a total reflector in the contracted beam would damage when a TEM_{00} output of 105 mJ was reached. This corresponded to a measured 26 mJ incident on the total reflector in a pulse of 25 ns duration with a beam of spot size $W_0 = 0.39$ mm. By contrast the prism reflector allowed a TEM_{00} output of 185 mJ to be reached before damage occurred. The energy incident on the reflector under these conditions was measured to be 47 mJ, i.e. approximately twice that which the multilayer mirror could sustain. The damage manifested itself as a very small speck at the interface where the beam division occurs. The vulnerability to damage at this location is probably a consequence of the standing waves formed at this interface [11].

The prism design of Fig. 2a is just one of a number of possibilities. McGeoch [6] and Vanherzeele [7] have used an arrangement where one has access to the location where the counter-propagating beams cross from one prism to the other (having exited from Brewster angle faces) as in Fig. 3. A passive mode-locking cell can then be placed at this location to allow colliding pulses. A further advantage of this prism arrangement is that it suppresses reflections where the beams cross. (If these are not suppressed then one cannot ensure equal amplitude counter-propagating waves recombining at the interface.) In our design the reflections were suppressed by using an appropriate choice of the interface spacing, however if one is free from this design constraint then one can consider the possibility of a variable spacing between the two prisms, controlled for example by piezoelectricity.

Such spacing control is made much more practical by avoiding the exacting requirements on spacing that are implied by FTIR beam splitting. By ranging the spacing the reflectivity can be adjusted, at any operating wavelength, from zero

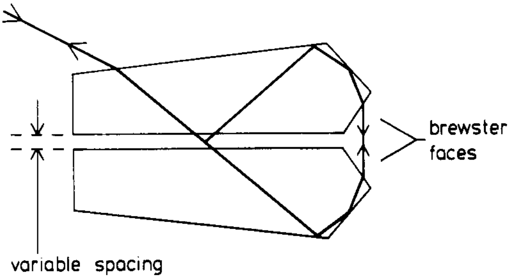

Figure 3 A reflector design tunable over the transmission range of the prism material.

to 100%. The range of operating wavelengths is determined by the transmission range of the prism material. Thus in the case of fused silica this would offer a tunable reflectivity from the UV to the near IR with a damage threshold in excess of that offered by multilayer reflection.

In conclusion we have constructed and tested an anti-resonant ring prism reflector of high reflectivity and high damage threshold. Used as the total reflector in a telescopic resonator it has allowed 150 mJ TEM_{00} output to be reliably achieved in a Q-switched NdYAG laser. Damage to the prism did not occur until the output energy reached a level of 185 mJ. The damage threshold under these conditions is approximately twice that of the best available multilayer reflector. By avoiding reliance on frustrated total internal reflection at the beam splitter interface a greater design freedom is achieved, and by providing a variable gap between the prisms this device could offer a reflectivity which is controllably variable between zero and 100% for any wavelength within the transmission range of the prism material.

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