Monolithic, unidirectional single-mode Nd:YAG ring laser

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We have built a nonplanar ring oscillator with the resonator contained entirely within a Nd:YAG crystal. When the oscillator was placed in a magnetic field, unidirectional oscillation was obtained with a pump-limited, single-axial-mode output of 163 mW.

In this Letter, we describe a new solid-state laser design that achieves high single-mode output power by using a unidirectional nonplanar resonator. Excellent frequency stability is achieved because the ring resonator is constructed from a single Nd:YAG crystal. We refer to the design as a MISER (Monolithic Isolated Single-mode End-pumped Ring) design. We developed this source as an oscillator for a long-range coherent Doppler anemometer.[1] Other applications areas include coherent communications, coherent optical radar, and inertial rotation sensing.

Ideally, a continuous-wave homogeneously broadened laser should oscillate in a single axial mode. The laser transitions in Nd:YAG are primarily phonon broadened, so the assumption of homogeneity is met. However, when a Nd:YAG laser is contructed with a standing-wave linear resonator, the threshold of the second axial mode is near that of the first. At the nulls of the standing wave created by the initial axial mode, stimulated emission does not take place, and the gain is not saturated. This spatially modulated gain, termed spatial hole burning, allows other axial modes to reach threshold and oscillate.[2]

A unidirectional ring resonator has no standing wave, and therefore spatial hole burning is eliminated. Much higher single-mode power is available from a ring than from a linear resonator even without the addition of selective loss elements, such as étalons. Successful high-power, single-mode operation of unidirectional rings has been achieved with arc-lamp-pumped Nd:YAG oscillators[3] and with commercial dye lasers.[4]

Excellent frequency stability is possible when the resonator of a Nd:YAG laser is monolithic, that is, when it consists of reflective coatings applied directly to the surfaces of the Nd:YAG. Even better stability is possible when the pump source of the laser is a laser diode with stable output power. We recently reported a laser-diode-pumped Nd:YAG rod laser that has a frequency jitter in 0.3 sec of less than 10 kHz.[5] Because of spatial hole burning, output power in a single axial mode has been limited to 8 mW.

The objective of this work is to combine the advantages of ring lasers and monolithic lasers by constructing a unidirectional resonator entirely internal to a single crystal of Nd:YAG. The conventional way to design a unidirectional laser is to include a polarizer, a Faraday rotator, and a nonmagnetic polarization rotator, such as a half-wave plate in the resonator. All three of these functions, which together form an optical diode,[6] are incorporated into the MISER resonator design. As is shown in Fig. 1, the resonator is a single block of Nd:YAG incorporating four reflecting surfaces, which act as mirrors. The front face is convex to provide resonator stability and is coated to be a partially transmitting output coupler. The other three faces are flat and totally internally reflecting.

Most ring lasers use a resonator that is entirely within a plane. There are sometimes advantages to a nonplanar geometry that are worth the greater complexity. Dorschne at Raytheon has described a nonplanar helium–neon ring laser that, when used as a gyroscope, overcomes the problem of self-locking or lock-in.[7] Researchers in the Soviet Union have built nonplanar Nd:YAG ring lasers and have studied the mode structure, temporal dynamics, and polarization of these lasers.[8] Biraben[9] suggested that single-mode dye lasers

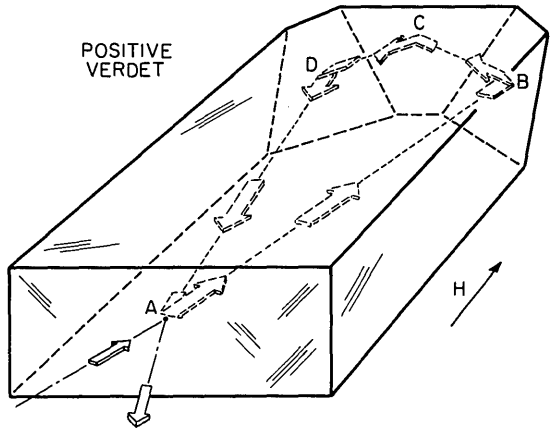


Fig. 1. The MISER laser design. Polarization selection takes place at the curved, partially transmitting face (point A). At points B, C, and D, total internal reflection occurs. A magnetic field H is applied to establish unidirectional oscillation. Magnetic rotation takes place along segments AB and DA. The focused pump laser beam enters the crystal at point A, and the output beam emerges at the same point.

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be constructed with a nonplanar ring-resonator geometry, for reasons similar to ours with the laser described here.

The nonplanarity of the MISER laser creates an effect that is analogous to rotation by a half-wave plate. The planes of incidence of the corner faces B and D are at an angle R to the plane of incidence of the front face. The plane of incidence of the top face is almost perpendicular to those of the corner faces. The rotation of the planes of incidence results in a net polarization (and image) rotation of $2R$ for a full round trip in the resonator.

The MISER design uses the Nd:YAG itself as a Faraday rotator. When there is a magnetic field applied along the long dimension of the Nd:YAG block, Faraday rotation takes place along the resonator segments AB (from the front face to the first corner) and DA (from the second corner back to the front face.) For one of the two traversal directions of the ring, the Faraday rotation subtracts from the polarization rotation that is due to the nonplanar design, whereas for the other direction, rotation is increased.

Nonnormal incidence on the output coupler face serves as the polarizer in this resonator. The P polarization is more strongly transmitted at the output coupler face, as the angle of incidence is not normal. The presence of this linear polarizer in the resonator favors the oscillation of polarization modes that are close to the S polarization. The oscillation cannot be in the linear S polarization, because in general any net rotation of polarization makes a linearly polarized mode impossible. The MISER would oscillate in a circular polarization if not for the birefringence that is due to the total internal reflection at points A, B, and C. This birefringence forces an elliptical polarization. If net rotation is reduced, then a polarization nearer pure S polarization becomes possible, and output coupling is reduced. When a magnetic field is applied, Faraday rotation cancels some of the geometrical rotation for one of the traversal directions, and the ring oscillates in that direction. A change in the sign of the magnetic field reverses the oscillation direction.

We have used Jones-matrix calculus to find numerically the eigenpolarizations and the difference in output coupling for the two directions of traversal. Our calculations show that when the magnetic rotation is small, maximum differential coupling occurs for an out-of-plane angle R of about 20°. At this angle the polarization is elliptical, with 89% of the power in the S polarization.

We have designed and constructed a MISER laser using Nd:YAG. The dimensions of the finished block were 38 mm × 13 mm × 3 mm. The angle of incidence at the output coupler was 7.8°, and the angle R between the output coupler plane of incidence and the corner face plane of incidence was 20°. All angles were specified with a tolerance of 0.08° (5 min). The output coupler was coated to be 99.2% reflecting in the S polarization and 98.8% reflecting in the P polarization at the angle of incidence used. The curvature of the output coupler face was 110 mm. For single-mode operation the crystal was placed in the field of a permanent magnet of 0.27-T average field. We measured the Verdet coefficient of Nd:YAG to be 103°/T m (Ref. 10), so the magnetic rotation in the segment AB is 1.1°. The differential loss between the two directions of traversal was calculated to be 0.01%.

The MISER laser was end pumped using an argon-ion laser (operating at 514.5 nm) focused with a 10-cm lens. The MISER threshold was reached at 0.15 W of pump power, and the slope efficiency was 5%. The transverse mode could always be limited to TEM_{00} by correctly aligning the pump laser and the ring resonator.

A Fabry–Perot étalon of free spectral range 1 cm^{-1} was used to observe the axial-mode structure. With a magnetic field present, oscillation was unidirectional, single mode, and stable. An interferogram of the single-mode output is shown in Fig. 2(a). Without a magnetic field, oscillation was bidirectional, multimode, and extremely noisy. Figure 2(b) is an inteferogram of the laser output without the magnetic field present.

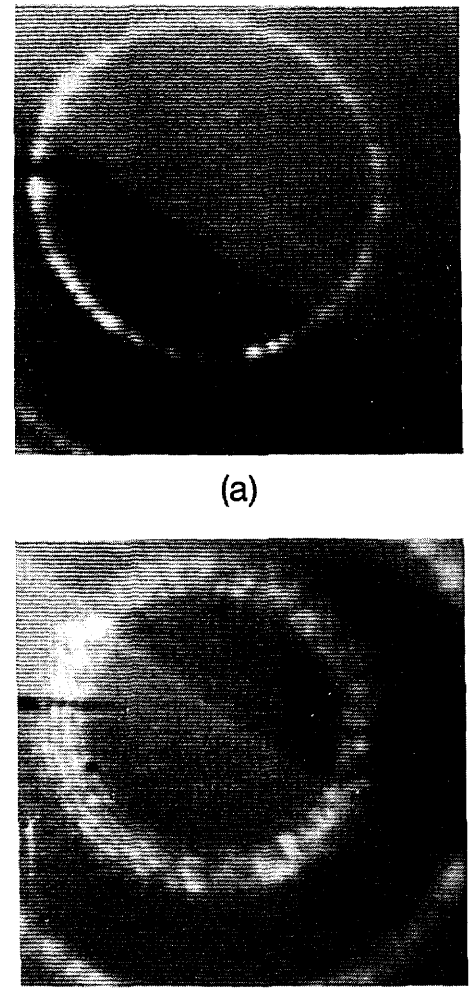


Fig. 2. (a) An interferogram of the MISER output with the magnetic field present, showing a single axial mode. (b) With the field removed, oscillation occurs in five axial modes. The free spectral range of the interferometer is 1 cm^{-1}; mode spacing is 0.064 cm^{-1}.

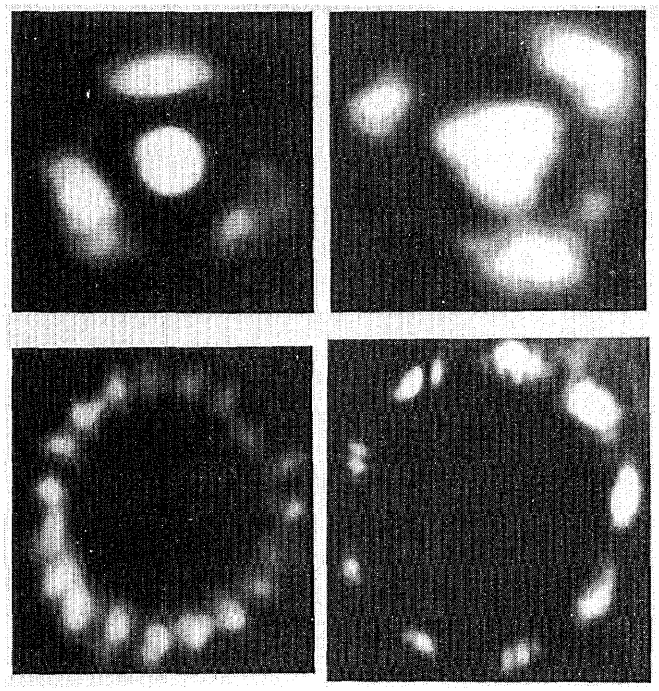


Fig. 3. The image rotation of a nonplanar resonator creates nonrectangular transverse-mode patterns. Four are pictured here.

With a field present, the MISER oscillated cw in a single direction and in a single mode up to an output power of 109 mW, which occurred at a 2-W pump power. At that level of pumping, bidirectional and multimode operation began. The output beam appeared to be badly distorted, indicating substantial thermal birefringence within the crystal. When a chopper was used to reduce the pumping duty cycle to 50%, single-direction, single-mode output was maintained up to the pump power limit of 3.1 W. Output at 1064 nm was 163 mW.

We also constructed and achieved unidirectional oscillation in a MISER using neodymium-doped gadolinium gallium garnet (Nd:GGG). Its dimensions were identical to those of the Nd:YAG MISER. The substantially greater Verdet constant of Nd:GGG (Ref. 10) is an advantage for this material. Detailed measurements were not made.

We made a beat-frequency measurement of the frequency stability of the argon-pumped MISER laser relative to a monolithic-rod Nd:YAG laser.[5] Jitter of 3 MHz in 1 sec was observed. Smaller MISER designs, when pumped with a semiconductor diode laser, should provide substantially better frequency stability.

When the pump beam is misaligned, higher-order transverse modes appear. The image rotation of the ring resonator breaks the rectangular symmetry of conventional resonators and leads to some unfamiliar transverse-mode patterns. Figure 3 contains photographs of some of the modes observed.

High scatter loss and low output coupling severely limit the efficiency of the MISER laser that we have tested. A 1/3-scale or smaller MISER design that uses low-doped, low-scatter Nd:YAG should improve efficiency and reduce threshold to the point that semiconductor laser-diode pumping would be possible. We believe that the present 109-mW limit on cw single-mode output is caused by thermal birefringence. Since any thermal effect is proportional to pump power, greater efficiency should lead to proportionally higher cw single-mode output power.

A laser-diode-pumped MISER laser could be a compact, efficient, and rugged high-power single-axial-mode oscillator. Applications include coherent communication through free space or through fibers using the 1321-nm transition of Nd:YAG. There may be remote-fiber-sensing applications for which the power available from a single-mode helium–neon laser is insufficient. If extreme frequency stability is achieved, then a MISER laser could be used as a compact and rugged ring-laser gyroscope. Stabilization may be possible by electrically tuning the magnetic field. There is a round-trip phase change that depends on polariztion rotation, and we have calculated that in Nd:YAG this will lead to a magnetic tuning coefficient of 20 MHz/T. Since a unidirectional ring laser is naturally isolated from light scattered back into the resonator from external optics, excellent frequency stability may be possible.

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