A TUNABLE F_2^+ - COLOR CENTER RING LASER

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Abstract

The design and development of an F_2^+ color center ring laser is described. Special emphasis is placed on the design of the undirectional device, single mode tuning techniques, and characterization of the long term stability of the F_2^+ color center laser. Single frequency operation has been achieved from 0.83 to 1.04 μm with an ouput power exceeding 1 w at 0.92 μm using an F_2^+:LiF crystal.

Introduction

The spectral range, tunability, and efficiency of the F_2^+ laser make it a nearly ideal source for applications in atomic and molecular spectroscopy,[2] fiber optics research, and frequency mixing schemes. CW laser emission from F_2^+ and F_2^+-like centers presently cover the range from 0.82 μm to 2.5 μm, with typical output powers exceeding one watt.[1-3]

Our work has focused on developing the F_2^+ laser as a useful spectroscopic light source. The ring laser is more efficient for single mode laser operation and is easier to tune than a linear laser.[4] Special emphasis has been placed on single mode tuning techniques, the design of a unidirectional device for the ring resonator, and characterization of the long term stability of the F_2^+ laser. Most of the work was performed using LiF:F_2^+ color center crystals which lase from 0.82 to 1.05 μ.

Design of Ring Laser

The F_2^+ color center ring laser is shown schematically in Fig. 1. The optical path is in a figure-eight configuration, traveling through the F_2^+ crystal, a prism and two etalons, and a unidirectional device consisting of a Faraday rotator and a c-axis quartz plate. The cavity is designed around a compact laser head,[5] which consists of a vacuum chamber with two bellow-mounted totally reflecting mirrors, a cold finger mounted to a translatable liquid nitrogen dewar, and two Brewster window exit ports for laser beams. The color center crystal is mounted at Brewster's angle to the cold finger.

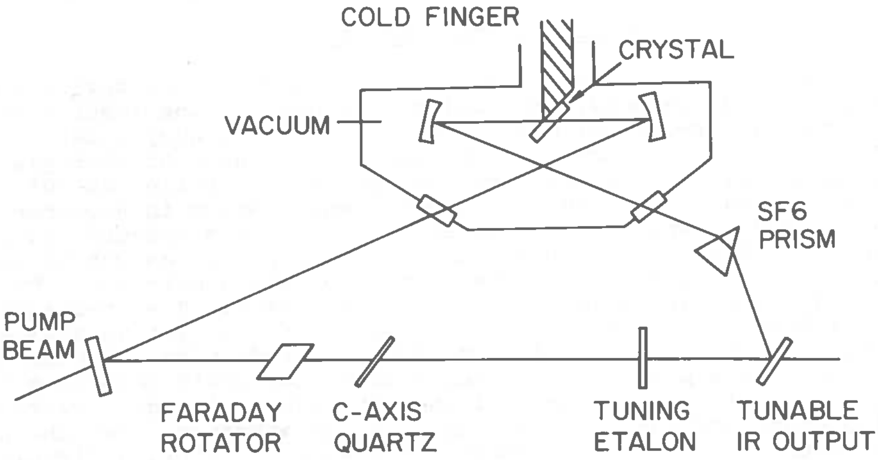

Fig. 1. F_2^+ color center ring laser configuration

The laser is collinearly pumped through one of the flat folding mirrors, which is dichroically coated for high reflectance over the lasing range of LiF (0.82 to 1.05 μ), and high transmittance for the krypton pump laser at 647 nm. The pump beam is focused into the crystal by one of the silver coated curved folding mirrors (R = 75 mm).

The ring laser has the advantage over a linear standing wave laser that it inherently operates in a single mode with only moderately dispersive tuning elements. However, the requirement that the laser will scan smoothly from one to the next cavity mode ($\Delta\nu$ = 200 MHz) necessitates using at least one selective element. Coarse tuning of the ring laser is accomplished using a Brewster-cut SF6 glass prism. The prism is simple to use, introduces few losses, requires no internal adjustment, and has a broad monotonic wavelength dispersion. Tuning is accomplished by tilting the output coupler. In order to eliminate changes in the output beam direction with changes in wavelength, the output coupler is mounted on a pivot arm which displaces the mirror appropriately as it is tilted. A typical prism tuning curve for the LiF:F_2^+ laser is shown in Fig. 2. The tuning range extends from 835 nm to above 1040 nm, and depends somewhat on the cavity Q, as is clearly shown by the two curves due to different output couplers. The rapid fall-off of power on the short wavelength side is due in part to a reduction of reflectivity of the dielectric cavity mirrors.

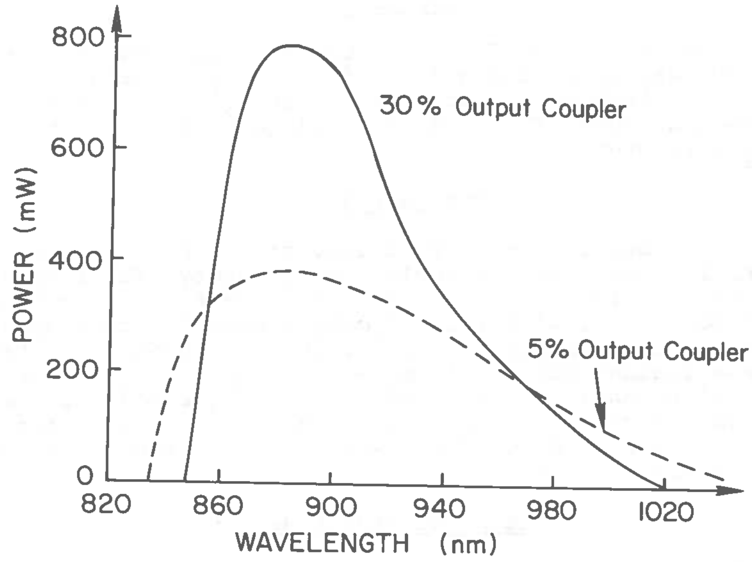

Fig. 2. Power tuning curves for the LiF:$_2^+$ ring laser

With the unidirectional device and prism in the ring cavity, the laser operated in a single mode with a jitter of 60 GHz. Stable single mode operation was achieved when an uncoated 0.12 mm fused silica etalon (FSR ≈ 800 GHz) was added to the cavity. This etalon did not have sufficient dispersion to scan the laser from one to the next cavity mode. A second etalon (1.0 mm, 60% R) was found to give smooth tuning over every cavity mode.

Unidirectional Operation

The crucial element in a ring laser is an "optical diode,"[6] the device which forces the laser to operate in one direction only. Without such a device, the laser alternately switches direction. The unidirectional device consists of a Faraday rotator and a c-axis quartz plate (see Fig. 1). The Faraday rotator was a 3 mm length of FR-5 glass (Hoya Glass Corporation), ¼" in diameter, with the ends cut and polished parallel at 30° to the rod axis to allow Brewster orientation in the cavity. The rod was mounted in a permanent cylindrical magnet with a field of 3200 gauss. The net rotation at 1 μm was measured to be 1.9 degrees.

For use as a reciprocal rotator, a crystalline quartz plate was cut so that the c-axis was at Brewster's angle inside the plate. The plate was approximately 0.3 mm thick, producing a 2° rotation of the polarization of a transmitted beam. Brewster surfaces were used because of their low insertion loss and to avoid etalon effects. Two unusual effects were observed: first, the laser operated stably and without a reduction in power with the c-axis plate removed; and second, the pump polarization orientation could determine the direction of laser operation. These effects can be explained through a straightforward calculation of the polarization eigenstates of the resonator using Jones matrices. For the purposes of the calculation, the resonator was assumed to contain a Faraday rotator, a circular phase plate (c-axis quartz), and a partial polarizer p. Figure 3 shows the round trip loss and state of the polarization inside the resonator for three values of p as a function of the net rotation of the unidirectional device. Several interesting features are apparent in Fig. 3.

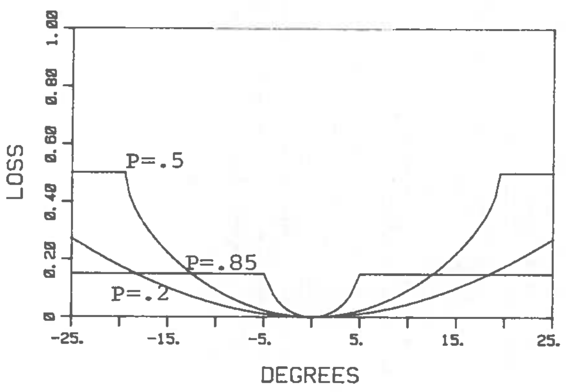

Fig. 3. (a) Round trip loss

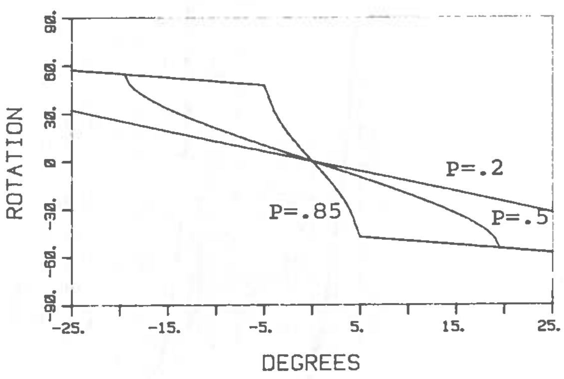

Fig. 3. (b) State of polarization in the ring resonator as a function of net rotation of the Faraday isolator

First, the losses increase with net rotation up to a point, then remain fixed at a value (1-p). Second, for small angles, the losses are much greater for weak polarizers than they are for strong polarizers. For a weak polarizer, the polarization angle is incremented every round trip, until eventually the loss induced by the polarizer is equal to the increase in the s-component on going through the rotators. For a strong polarizer, the polarization does not deviate far from the Brewster plane. From the loss curve, it is seen why the c-axis plate has little effect on the threshold or output power of the laser. A change of two degrees for the p = .2 case, which is close to the actual laser value which corresponds to 12 Brewster surfaces, causes an insignificant change in losses compared to the output coupler (~10%) and the crystal (~10%). As mentioned above unidirectional operation was also observed with only the Faraday rotator inside the cavity. In this case, the necessary reciprocal rotation is obtained from stress induced birefringence in the crystal and various phase shifts by the cavity mirrors. In order to explain how the pump polarization can affect the lasing direction, it is necessary to determine the gain of an F_2^+ crystal as a function of the relative angle between the polarization of the pump laser and the cavity mode. Figure 4 shows the results of such a calculation. As expected, the calculated gain is maximum when the pump and laser polarization are parallel. Lasing will occur for such an anisotropic medium at the point where the ratio of gain to loss is a maximum. For a resonator containing a Faraday isolator, the two directions of propagation will have different polarizations. It is thus possible to increase the gain for one direction as opposed to the other simply by rotating the pump polarization.

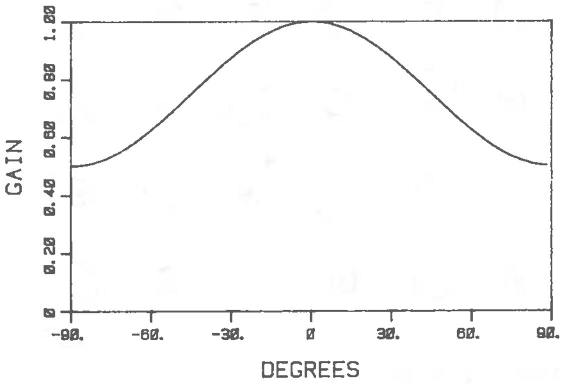

Fig. 4. Gain of the F_2^+ center crystal as a function of the relative angle between pump and laser polarization

F_2^+ Color Center Stability

A present difficulty of the LiF F_2^+ laser is the irreversible loss of gain in the crystal with sustained operation. Figure 5 shows a strip chart record of the output power of an OH^- doped LiF F_2^+ laser taken at two different spots on the same crystal. Such variation in behaviour makes it difficult to characterize the decay in F_2^+ center crystals. Three

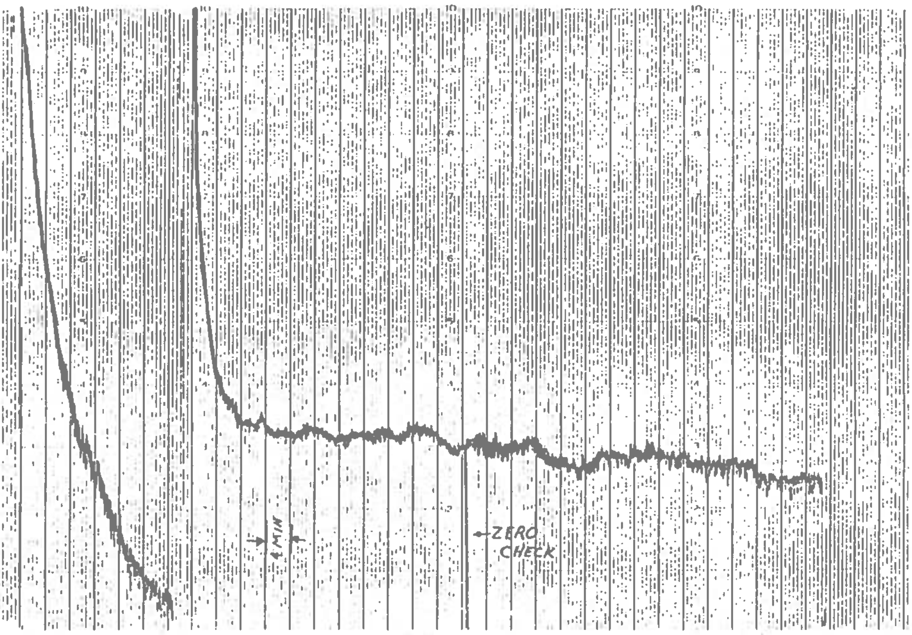

Fig. 5. Strip chart record of the output of an operating F$_2^+$ laser. Each major division represents 4 minutes.

possible mechanisms have been suggested as the cause of this degradation: electron capture, by an F$_2^+$ center; "bleaching" by rotation of the center; and finally, aggregation of the F$_2^+$ center to higher order centers. Figure 6 shows an example of charge capture: an F' center ionizes and the free electron is captured by an F$_2^+$ center neutralizing the center. This effect can be slowed by incorporating a sufficient density of electron traps[2] or by ionizing the F$_2$ center through a selective two step photoionization process.[7] Both methods were tried and were observed to have no effect on the laser power or threshold. Therefore, we conclude electron capture is not a problem in the LiF system.

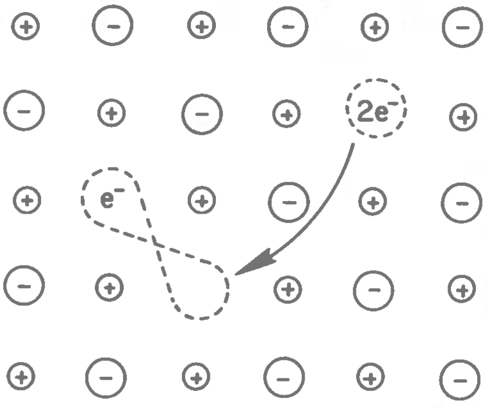

Fig. 6. Possible mechanism for neutralizing a F$_2^+$ center through charge capture

A second mechanism is shown in Fig. 7, where an F$_2^+$ center reorients itself via two photon excitation from the pump laser.[5] This can have two effects. First, it can reduce the effective dipole moment of the center along the laser polarization. This effect can be reversed and should cause no long term effects. The second, more deleterious effect is that the center can migrate through the lattice via repeated reorientations until it meets another defect and forms a higher order aggregate. We observed that the more densely colored LiF crystals decayed much faster than lighter crystals lending support to this aggregation hypothesis. It should be noted that crystals by present preparation techniques typically last 7 days before degrading to unusable levels making the decay more of an experimental inconvenience rather than a barrier to application of the laser.

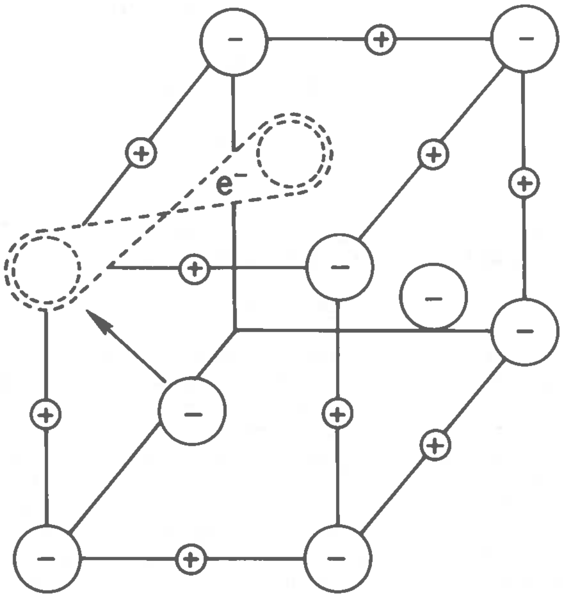

Fig. 7. Reorientation of an F_2^+ center

Conclusions

From the above discussion, several important considerations in the design of an F_2^+ ring laser are apparent.

1) The resonator should have a minimum number of Brewster surfaces for stable unidirectional operation.
2) The cavity should have a large beamwaist at the crystal to reduce pump intensity, and therefore reduce two photon absorption effects.
3) The crystals should be lightly colored to reduce the chances of aggregation. If the optical density is too low, the crystal can be made thicker.
4) A sufficient density of electron traps should be incorporated into the crystal to reduce charge capture effects.

The F_2^+ ring laser is a very effective broadly tunable single frequency radiation source in the near infrared, in particular when interfaced to a minicomputer in the same manner as described in Ref. 8. The F_2^+ laser was tunable in a single mode over the entire tuning range of the color center crystal. When using a prism and two etalons the operation and design criteria for a unidirectional device were discussed, and experimental evidence was obtained which leads us to conclude that aggregation is the probable cause for the limited active lifetime of the F_2^+ laser with currently available crystals.

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