Laser cavity for generation of variable-radius rings of light

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We report a laser cavity that has a ring as its output mode. The radius of the ring can be scanned by tuning the laser frequency. This design can be implemented in any tunable laser with large gain and can be useful when ring illumination patterns are needed. As an example, we demonstrate this new cavity configuration by using a side-pumped grazing-incidence dye laser.

It has been predicted that when the surface of a solid is illuminated by an optical field in the form of a rapidly collapsing ring, acoustic waves generated on the surface of the solid will focus as they propagate into the solid.[1] Such ring illumination patterns could be generated by passing a diverging laser beam through a rapidly scanned Fabry–Perot étalon, although most of the energy in the beam would be lost. Loss would be minimized, however, if the ring-generating optic was brought into the cavity, thereby modifying the output mode of the laser.

Unstable laser resonators are known to generate exotic output patterns.[2] For example, in a laser cavity defined by a plane mirror and a convex mirror, light will couple out by leaking over the rim of the convex mirror. This kind of laser has an output beam in the shape of a ring; however, the radius of the ring so generated cannot be easily changed.

In this Letter we report a novel unstable-resonator cavity design that has a ring output mode with the property that the radius of the ring can be changed by tuning the frequency of the laser. We demonstrate this by using a grazing-incidence dye laser. Our laser cavity is shown in Fig. 1. It is similar to the narrow-spectral-linewidth laser that has been studied earlier,[3] but in this version the output coupler is replaced with a negative lens and a Fabry–Perot étalon. Lasing occurs between the reflective surfaces of the étalon and the frequency selector, which is made up of a diffraction grating and a tuning mirror. The negative lens diverges the intracavity beam, thus causing the cavity to be unstable.

If the laser is operating at a single wavelength λ, and the étalon has a thickness d and an index of refraction n, then maximum transmission through the étalon will occur at the incident angle θ according to

$$2nd\cos(\theta) = m\lambda, \tag{1}$$

where m is an integer. In reciprocal length units (e.g., cm^{-1}), the quantity $1/(2nd)$ is the free spectral range (FSR) of the étalon. Because the beam is axisymmetric around the optical axis, the output of the laser is ring shaped.

Assume that a maximum transmission occurs at $\theta = 0$ when the laser is tuned to wavelength λ_0; then

$$2nd = m_0\lambda_0, \tag{2}$$

where m_0 is an integer. The angle of the next transmission maximum will be

$$\theta_0 = \arccos\left(\frac{m_0 - 1}{m_0}\right). \tag{3}$$

Other transmission maxima, corresponding to orders $m \le m_0 - 2$, occur at progressively larger angles. By tuning the laser to a shorter wavelength, one scans the $m = m_0$ order ring to a larger angle. To limit the laser output to operation on a single ring at all times and still maintain the maximum scanning range of the ring size, the negative lens in the cavity should be chosen so that the angular divergence of the beam is just below θ_0.

We have used a solid étalon with a FSR of $1.6\ \mathrm{cm}^{-1}$. For this étalon at $\lambda \approx 580$ nm, θ_0 is 0.0136 rad. In our setup described below, the half-angular divergence of the intracavity beam is measured to be 0.012 rad when an $f = -25$ mm lens is used in the cavity. Thus the condition just described is clearly satisfied.

A N_2 laser (337 nm) is focused by a 10-cm focal-length cylindrical lens to pump a stirred cell of 2.5×10^{-3} M solution of Rhodamine 6G dye in methanol. The active gain region is 1 cm long and approximately $2w = 0.1$ mm in diameter, resulting in a half-diffraction angle[4] of $\lambda/(\pi w) = 0.004$ rad for light emerging from the dye cell. The intracavity negative lens further increases this to 0.012 rad. We used an 1800-line/mm holographic grating that is 5 cm long. The center of the grating is approximately 7 cm from the dye cell. The étalon is on the opposing side of the dye cell, also approximately 7 cm away from the

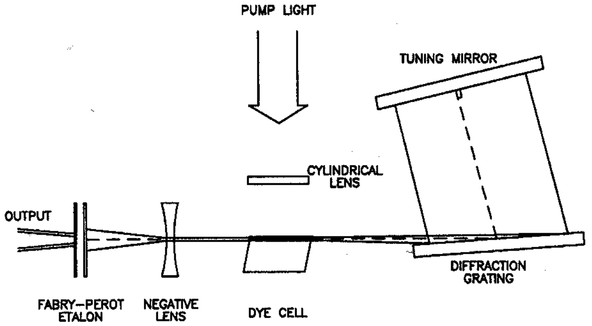

Fig. 1. Schematic of the laser cavity.

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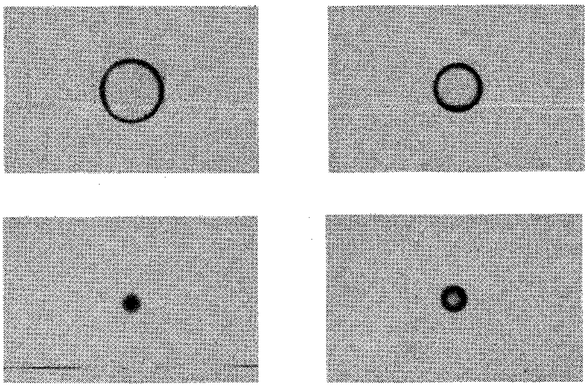

Fig. 2. Laser output mode as viewed in the focal plane of a lens external to the cavity when the frequency of the laser is tuned. Clockwise from top left: $\omega = \omega_0 \approx 17{,}240\ \text{cm}^{-1}$, $\omega = \omega_0 - 0.4\ \text{cm}^{-1}$, $\omega = \omega_0 - 0.8\ \text{cm}^{-1}$, and $\omega = \omega_0 - 1.2\ \text{cm}^{-1}$.

cell. The negative lens is roughly halfway between the cell and the étalon and is slightly tilted to prevent lasing off its surface reflection. None of the cavity parameters is critical, although shorter cavities are more efficient.

The spectral linewidth of this laser is approximately $0.1\ \text{cm}^{-1}$. The laser output is a single high-intensity ring when viewed in the focal plane of a lens ($f = 300$ mm) external to the cavity. The laser is continuously tunable. As the wavelength is tuned by rotating the tuning mirror, the output mode changes such that the ring radius is scanned. The lens external to the cavity is needed in order to map the output field, which occurs at specific angles defined by Eq. (1), into a sharply focused ring. Figure 2 shows the laser output mode at several frequencies within a FSR of the étalon.

It is worth noting that an alternative method of scanning the radius of the ring is to sweep the effective optical path length of the Fabry–Perot étalon while keeping the laser frequency constant. In some applications this may be a more attractive method.

Given that the objective is to produce a sharp ring pattern, several factors need to be considered in choosing the focal length of the internal lens and the FSR of the étalon. Étalons with large FSR require sizable beam-diverging angles. A large internal diverging angle generally means a more lossy cavity. However, large FSR étalons are less demanding on the laser spectral linewidth that is required to make a sharp ring. Stated another way, this means that étalons with small FSR require only minimal beam-diverging angles, but making a sharp ring requires that the spectral linewidth of the laser be small. In our setup we have also tested étalons that have FSR's of 0.67, 1.1, and $14.0\ \text{cm}^{-1}$. The results are consistent with the analysis given above.

We are currently working on integrating an electro-optic scanner into this cavity design, so that when it is used with a several-microsecond-duration $\text{Ti:Al}_2\text{O}_3$ laser, pulsed collapsing rings of light can be produced. Depending on the optical configuration, the intracavity scanner can be used to scan the laser frequency or the effective optical path length of the Fabry–Perot étalon. Electro-optical scanning is necessary here because the scanning speed that is required is higher than what can be provided by other scanning methods.

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