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Cooperative torus mode emission of O-ring lasers

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ABSTRACT
Deformable ring lasers were fabricated by dispersing fluorescent dye (rhodamine 6G) in silicone rubber rings, i.e., the so-called O-rings. When excited with a pulsed green laser, an O-ring of 750 μm diameter exhibited a stimulated emission with a threshold fluence of 20 μJ/mm². The wavelength and directionality of the emission were tunable by expansion or distortion of the ring with a needle. Because of this flexibility, the fluorescent peak of the O-ring lasers was not too sharp (a low-Q emission) and its wavelength differed slightly with individual rings. These features were advantageous for inducing a cooperative emission through an optical coupling of the rings. The optical coupling could be attained by exciting a cross-sectional circulation mode (torus mode), which the O-ring held in addition to the ordinary whispering gallery mode. When an O-ring was spitted with a glass fiber, for example, the torus mode coupled with the fiber mode, and consequently, the ring fluorescence emerged from the fiber end. Multiple O-rings, which individually exhibited a different emission wavelength, generated a single emission peak due to the optical coupling when they were arranged together on a split fiber.

I. INTRODUCTION
The progress of man-made machines depends on unremitting complication or miniaturization efforts in advanced technologies including computer-controlled systems and nano-fabrication processes. By contrast, living creatures unify a variety of individual components in a self-organized manner to attain a synchronized behavior, e.g., simultaneous glow of fireflies and periodic beating of cardiac muscles. These phenomena, i.e., the so-called “coupled synchronization” or “cooperative oscillation,” have been studied on the basis of the Kuramoto model.1–3 The recent trend toward “biologically inspired systems” has aroused interest in the synchronization of incoherent signal sources. That is, the concept of the coupled synchronization is instructive for the development of ordinary devices in various technical fields, although their functions are still far inferior to those of the sophisticated biological systems.

Construction of a coupled synchronization system needs multiple nonlinear oscillators with which a synchronized action is readily attainable. Of various physical or chemical phenomena, stimulated emission (laser emission) is one of the most useful nonlinear processes, since optical parameters allow simple, accurate measurements and optical resonators provide a readily adjustable coupling efficiency.4–6 In a recent optical technology, for example, a global coupling is used to synchronize vertical cavity lasers.7 It has been pointed out that high-Q resonators are difficult to synchronize and that an adjustable coupling efficiency facilitates the control of the synchronization process.7–10

In this study, we fabricate a “soft laser” that exhibits a low-Q emission at an indefinite wavelength. These characteristics are unfavorable for creating ordinary laser oscillators but suitable for constructing a cooperative oscillation system. Another important characteristic is a mass-production capability that allows a preparation of multiple resonators with slightly different sizes or features, since synchronization of identical resonators is too common to investigate and synchronization of widely different resonators is difficult to induce.

To meet these requirements, we create ring lasers by the use of organic dye and silicone rubber rings, i.e., O-rings that are commonly used for vacuum or mechanical sealing. Ring resonators realize a mirrorless laser emission due to the whispering gallery (WG) mode in which fluorescent light circulates along the periphery. A spread evanescent field of the WG mode facilitates the coupling with the adjacent ring or waveguide. Because of these advantages, micro-ring lasers have been fabricated with a variety of materials, e.g., semiconductors,11,12 oxides,13–14 or polymers,15,16 aiming at wavelength selection, slow-light propagation,17 reproduction of molecules,18 etc. The rings are usually prepared by the etching or molding processes, and accordingly, they have a cylindrical shape; i.e., the side
wall is perpendicular to the base. O-rings are distinguished from these cylindrical rings by their torus shape or circular cross section. The O-rings, therefore, hold a circulation mode in which light propagates along the cross-sectional circumference. This circulation mode, which may be called a “torus mode,” realizes an optical coupling at the inner surface of the ring. That is, if a ring is spitted with an optical fiber, for example, the torus mode couples with a fiber mode. A cooperative laser emission may be attainable if the O-ring lasers are arranged along an optical fiber like spit-roasted meat. This “spit coupling” is useful to monitor the torus mode emission at the fiber end.

The spit coupling relies on the deformability of the O-rings. Silicone rubber is a suitable material for creating flexible devices due to its deformability, molding (imprinting) capability, chemical stability, and nontoxicity. The high transmittance over the entire visible spectral range renders silicone a useful matrix for optical materials (dyes) and opto-fluids. Solid dye lasers, droplet lasers, and microfluidic lasers have been developed by using silicone to demonstrate their flexibility or tunability successfully. Another important feature of silicone rubber is a high molecular diffusivity, which realizes a post-curing dye dispersion. The dye dispersion has to be achieved after the ring formation, since dye molecules tend to suffer chemical or thermal damage during the curing or molding process of the matrix.

II. SAMPLE PREPARATION AND EXPERIMENTS

Two types of silicone rings with a different size were purchased for the experiments; i.e., the outer and inner diameters of the larger rings were 2.2 mm and 0.7 mm, and those of the smaller ones were 0.75 mm and 0.25 mm. As shown in Fig. 1(a), the rings were immersed in a 2-propanol solution of rhodamine 6G with a concentration of 0.05–0.5 mM (5 × 10⁻⁵–5 × 10⁻⁴ mol/l). The solution was heated to 60 °C for acceleration of the diffusion, and the immersion was continued for 30 min. As shown in Fig. 1(b), the entire ring was pigmented in 30 min; i.e., a uniform dye distribution was visible in the cross-sectional micrograph, which was taken with a sliced piece of the ring. Figure 1(c) shows an optical system for the measurement of the emission spectra. A frequency-doubled Nd:YAG laser pulse (532 nm wavelength, 5 ns duration) was used for excitation of the pigmented ring. The laser beam was expanded with a concave lens to create a uniform intensity distribution on the ring that was fixed on the needle tip. As shown in the lower-left photograph of Fig. 1(c), the ring (0.75 mm diameter) emitted yellow light during the excitation process. A convex lens collected the emitted light and a long-pass filter eliminated the scattered excitation beam. The lens created a magnified image (×10) of the ring side (the right photograph), which exhibited bright spots at the ring edges corresponding to the ordinary WG mode emission (light circulation along the ring periphery). An optical fiber with a core diameter of 0.4 mm scanned the image to measure the intensity distribution. Since the fiber moved with a 0.4 mm step on the magnified image plane, the spatial resolution on the actual ring was 0.04 mm. The received emission was measured by using a multichannel spectrometer, whose spectral resolution was 0.06 nm.

III. WG MODE EMISSION

Figure 2(a) exemplifies the emission spectra that were measured at the ring edge. A fluorescent peak appeared at 568 nm and grew as the pump pulse fluence was raised. Figure 2(b) shows the peak height and width (full width at half maximum) that were measured as raising the pulse fluence. The peak height increased nonlinearly and the width decreased rapidly at around 20 μJ/mm². This strong, nonlinear emission appeared only at the ring edges, which indicated that the stimulated emission took place in the
ordinary WG mode. When the pump fluence was below the threshold (20 μJ/mm²), no strong emission was visible at the edge, i.e., the emission intensity was uniform over the entire ring.

The deformation effects were examined by expanding the ring. As shown in the micrographs of Fig. 2(c), a needle was inserted in the ring hole to extend the diameter (maximum outer diameter: 1.20 mm). Figure 2(d) shows the distributions of the emission intensity (peak height) that were measured for the rings with the outer diameter of 0.75 mm or 1.00 mm. The horizontal axis shows the position on the ring side, i.e., the 1/10 scale of the fiber position on the magnified image plane. As mentioned above, the original ring (0.75 mm) exhibited a strong emission at around ±0.35 mm, i.e., in the vicinity of the ring periphery. These bright spots shifted outward as the ring expanded. When the outer diameter was 1.00 mm, the bright spots appeared at −0.44 mm and +0.48 mm, corresponding to the extended ring radius.

The ring expansion also induced a spectral peak shift. Figure 2(e) shows the spectral change during the expansion process. The emission peak of the original ring (0.75 mm) was located at 567 nm. When the outer diameter extended to 0.80 mm, the emission intensity increased whereas the peak wavelength shift was negligible (within the fluctuation of the soft laser). As the ring expanded further, however, the emission intensity decreased gradually and the peak shifted to a shorter wavelength. Figure 2(f) shows the diameter dependence of the peak wavelength during the expansion and contraction processes. The peak wavelength was tunable between 560 nm and 567 nm. Note that the peak wavelength of the original ring (567 nm) is different from those of the emission spectra (568 nm) in Fig. 2(a). The emission spectra usually exhibit a slight fluctuation like this, even if rings of the same size are prepared in the same fabrication process. That is, rings with the same fabrication history exhibit similar but not identical characteristics, since they suffer a deformation or influences from the surrounding materials. Consequently, the O-ring lasers exhibit a low-Q emission that is affected heavily by the adjacent rings or waveguides. Such irregularity and low Q-value are the features of the soft laser, and they facilitate the construction of a cooperative oscillation system.

Another experiment on the deformation effect was conducted by using the larger ring with the outer and inner diameters of 2.2 mm and 0.7 mm, which is shown in Fig. 1(b). As shown in Fig. 3(a), a metal plate with a 0.5 mm thickness and a 2.4 mm width was inserted in the ring hole to create an elliptical resonator. The excitation pulse was irradiated on the ring top, and the emission was measured from the side, as shown in Fig. 1(c). As the image in Fig. 1(c) shows, an original circular ring exhibited a symmetric fluorescence distribution, in which bright spots were located at the left and right edges. By contrast, the elliptical ring exhibited a nonsymmetric distribution that depended on the observation direction. The photograph in Fig. 3(b) was taken from the direction of θ = 40°. The right edge is the brightest, whereas the left edge is not brighter than the middle region. The dark region corresponds to the angular position of θ = 90°–140°. The light intensity distributions were measured in the same manner as those in Fig. 2(d). The ring was rotated to a selected angle (θ) so that the emission toward that direction was measured. Figure 3(c) shows the distributions of the emission intensity (spectral peak height) that were measured in several different directions. Regardless of the direction, the emission became the strongest at the ring edge, e.g., a position of 0.7 mm at θ = 0° and 1.5 mm at 90° corresponding to the short and long diameters (1.4 mm and 3.0 mm) of the elliptical ring. The emission peak height varied as the ring rotated; i.e., it became strongest at θ = 40° and weakest at 140°. This anisotropy was caused by the variation in the surface curvature. It was reported that elliptical resonators emitted fluorescence at positions with a small radius of curvature. Therefore, it is assumed that the leakage of the circulating light (the ordinary WG mode) is strong at the positions of θ = 40°–90°, where the radius of curvature decreases as the light beam propagates. Since a large portion of the beam leaks out in that region, the leak light (emission) intensity becomes weak in the downstream (θ = 90°–140°).

IV. TORUS MODE EMISSION AND COUPLING

Finally, experiments were conducted to pick up the torus mode emission (the cross-sectional circulation mode). In a previous study, we reported that the WG, radial, and axial modes compete with one another in a cylindrical resonator. Since the O-ring laser holds the torus mode in addition to these conventional modes, it is difficult to distinguish one from the others by using the optical system of Fig. 1. The torus mode light can be picked up selectively if the ring is coupled with an optical fiber at the inner surface (spit coupling), as shown in the inset in Fig. 4(a). A silica-glass optical fiber that was used in the experiment was 0.8 mm in core diameter, 1.0 mm in cladding diameter, and 0.25 m in length. The original outer and inner diameters of the ring were 2.2 mm and 0.7 mm, respectively, and the outer diameter was extended to 2.4 mm by the insertion of the fiber. The rings were pigmented before the fiber insertion by the use of the solutions whose dye concentration was varied between 0.05 mM and 0.5 mM. The dye concentration in the ring was difficult to evaluate, although it changed depending on that of the solution. We therefore distinguished the rings with reference to the dye concentration of the solution in which they were pigmented.

The pump laser beam was shaped with two cylindrical lenses (focal lengths: 100 mm and ~20 mm) so that an elliptical beam irradiated the fiber side; i.e., the beam diameter was 10 mm in the axial direction of the fiber and 2 mm in the radial direction. When a ring was spitted with the fiber, therefore, the upper half of the ring side was irradiated and the torus mode emission in the ring cross section coupled into the fiber, as shown in Fig. 4(a). The emission was

FIG. 3. (a) Top view of an O-ring (original outer diameter: 2.2 mm) that was expanded with a thin metal plate (2.4 mm width). Emission was measured in various directions. (b) Side view of the light emitting ring. The photograph was taken in the direction of θ = 40°. (c) Emission intensity distributions that were measured in various directions, θ.
measured at the fiber end by using the spectrometer. Figure 4(a) shows the emission spectra that were measured for the rings with a varied dye concentration. As the concentration increased, the emission peak shifted to a longer wavelength. The strong emission was attained with a ring that was fabricated in the solution of 0.3 mM. Figure 4(b) shows the peak height and width of this ring as a function of the pump beam fluence. The peak height increased nonlinearly with the fluence and the peak width decreased correspondingly. The other rings exhibited a similar dependence on the pump beam fluence. This result indicated that the stimulated emission took place by a low-Q emission, deformability, tunability, variation of individual properties, and susceptibility to the surroundings. The torus mode emission and the spit-coupling are also distinguished functions of the O-ring laser. On the basis of these features, cooperative torus mode emission was demonstrated with the O-rings that were spitted by an optical fiber. These characteristics of the O-ring laser will open up a new research field, since stimulated emission is a useful nonlinear process for creating an analog to natural or biological systems.

V. CONCLUSION

The dye-doped O-ring acts as a soft laser that is characterized by a low-Q emission, deformability, tunability, variation of individual properties, and susceptibility to the surroundings. The torus mode emission and the spit-coupling are also distinguished functions of the O-ring laser. On the basis of these features, cooperative torus mode emission was demonstrated with the O-rings that were spitted by an optical fiber. These characteristics of the O-ring laser will open up a new research field, since stimulated emission is a useful nonlinear process for creating an analog to natural or biological systems.

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