Inexpensive operating system for whispering-gallery-mode laser using dye-doped solid small spheres

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(Received 17 June 1992; accepted for publication 17 November 1992)

A simple and inexpensive system is reported for a whispering-gallery-mode (WGM) laser using a dye-doped solid small sphere. A WGM laser is pumped by a compact transversely excited atmospheric (TEA) UV N₂ laser. Experiments using the inexpensive system and some features in the WGM laser are demonstrated.

I. INTRODUCTION

A dielectric sphere possesses natural modes of oscillation at characteristic frequencies corresponding to specific size-to-wavelength ratios defined as the size parameter. Recently, the advantages of the spherical resonator have been pointed out because of the very high-quality factor (Q value) of electromagnetic whispering-gallery mode (WGM)¹ or morphology-dependent resonance (MDR) in the dielectric sphere with micrometer-sized droplets^{2,3} or solid particles.^{4,5} In addition, the high Q value of spherical cavities has been shown to provide us very low-threshold lasers.^{2,3} This paper reports a simple and inexpensive system for a WGM laser using dye-doped solid spheres.

II. APPARATUS

A. WGM laser system

A schematic diagram of an experimental setup is shown in Fig. 1. A transversely excited atmospheric (TEA) UV N₂ laser (337 nm) is used to excite a spherical dye-doped WGM laser (DD-WGM), focusing the pumping UV N₂ laser beam with a quartz spherical lens (QSL) after beam shaping through a circular beam aperture (CA).

Emission light from the DD-WGM laser is detected by a detector system (spectrum analyzer or biplanar phototube/oscilloscope system) via quartz-glass optical fiber. The position of the DD-WGM laser, which is fixed on the tip of a needle installed on a mechanical stage, is adjusted finely in the vicinity of the focal point of the QSL with ~ 5 cm focal length.

B. TEA UV N₂ laser for WGM-laser excitation

The UV N₂ laser for the DD-WGM laser pumping is open-air TEA type⁶ with a water-flown spark-gap switch (WG), which has a 12 cm active length and 3 mm spacing of the main-discharge electrodes (ME). A schematic structure of the TEA N₂ laser is shown in Fig. 2. The flat-plate Blumlein circuit (BC), which is composed of Mylar sheet (150 μ m thick, $\sim 20 \times 20$ cm²) and two upper and one lower copper plates, serves as an energy storage capacitor

of main discharge for the N₂ laser operation. This capacitor is charged in a series of pulses by LC-inversion circuit. The capacitance of the flat-plate BC is 350–400 pF in each side. The LC-inversion circuit (LC-IC) is composed of a two-stage ceramic capacitor ($C=4$ nF) and a pressurized air-filled triggered gap switch (G1).

In order to obtain stable glow discharges in atmospheric air, a simple preionization technique for main discharges is adapted. The discharge-electrode structure with the preionization circuit, which is mounted on the upper plates of the flat-plate BC, is shown in Fig. 3. The preionization circuit composed of aluminum foils and Mylar sheets leads the pilot discharge between the ME. Stable glow discharge between the ME can be realized by adjusting the CP length (see Fig. 3) and/or the overlaps (δ) of the inner/outer aluminum foil in the preionization circuit.

C. Preparation of a DD-WGM laser

A spherical dye-doped whispering-gallery-mode (DD-WGM) laser is prepared by dyeing the polystyrene or ion-exchange resin [with a small diameter (~ 40 – 800 μ m)] in rhodamine 6G (RH-6G) ethanol solutions (10^{-5} – 10^{-3} M). Figure 4 shows a microphotograph of the dye-doped spheres, with ~ 70 μ m diameter in (a) and fixed on the tip of a needle with ~ 700 μ m diameter in (b), respectively.

III. EXPERIMENTAL RESULTS

The laser-pulse waveforms of the TEA UV N₂ laser and DD-WGM laser were measured with a calibrated Hamamatsu Photonics R1193U-02 biplanar phototube and a Hewlett-Packard 1744A storage oscilloscope (100 MHz) system. The spectral characteristics of the DD-WGM laser output pumped by the TEA UV N₂ laser were analyzed with an optical multichannel analyzer (OMA; Hamamatsu Photonics PMA-10).

A. TEA UV N₂ laser characteristics

Under these conditions: suitable adjustments in the preionization circuit, 15 kV applied voltage, the N₂ gas flows at a rate of ~ 10 cm³/min between the ME from the

FIG. 1. Experimental setup of WGM laser system. UV-N₂: TEA UV N₂ laser, CA circular beam aperture, QSL quartz spherical lens, DD-WGM spherical dye-doped WGM laser.

back (with an Al-coated flat back-reflector) to the front, the TEA UV N₂ laser typically exhibits 1.3 ns full width at half maximum (FWHM) and 3 kW peak power at 337 nm in the second positive band of N₂ molecules (measured with a 275 MHz real-time oscilloscope and with a Photodyne 66XLA power meter, respectively). Figure 5 shows the typical N₂ laser pulse waveform, which is exhibited as a band-limited pulse by a 100 MHz storage oscilloscope.

B. DD-WGM laser characteristics

1. Waveform and lasing pattern characteristics of DD-WGM laser output

By finely adjusting the position of the dye-doped sphere in the vicinity of the focal point of the QSL, many varying bright-reddish full moon and crescent patterns in the near field were observed. In the far field, however, such patterns were never observed. This implies that the laser emission from the dye-doped sphere emerges in all radial directions in direct contrast to the unidirectional beam of low divergence produced by usual dye lasers.³ The DD-WGM laser serves as a coherent point source emitting in all directions in the far field.⁷ Figure 6 shows the near-field pattern (on a white paper at about 10 cm apart from the dye-doped sphere with $\sim 600 \mu\text{m}$ diameter) from the UV N₂ laser pumped DD-WGM laser. The direction of the pumping N₂ laser (not shown) is from right to left horizontally through the DD-WGM laser fixed on the tip of a needle. The fluorescence from the white paper irradiated by the N₂ laser beam after passing through the DD-WGM laser is observed on the left. Figure 7 shows the appearance of the light emitted in all radial directions from the DD-WGM laser; it corresponds to the lower-exposure case than that in Fig. 6.

Under various N₂ laser pumping intensities induced by neutral density filters, the laser waveforms measured with a biplanar phototube and a 100 MHz storage-oscilloscope

FIG. 2. Schematic structure of an open-air TEA UV N₂ laser. G1: pressurized air-filled triggered gap switch, LC-IC LC-inversion circuit, BC flat-plate Blumlein circuit, ME main-discharge electrode, WG water-flow spark-gap switch.

FIG. 3. Discharge-electrode structure with the preionization circuit. ME main-discharge electrode, AF aluminum foil, MS Mylar sheet.

system are shown in Fig. 8(a). The rise and fall of the fluorescence waveforms [Fig. 8(b)] with much lower pumping intensity are clearly different from that of Fig. 8(a). The waveforms in Fig. 8(a) follow the pumping N₂ laser pulse, while the one in Fig. 8(b) exhibits the slower rise and fall.

2. Spectral characteristics of DD-WGM laser output

In order to verify that the laser operation was due to WGM, we examined the mode structure of the emission spectra from the dye-doped sphere. The dye-doped spheres were placed on a glass plate under a microscope. Figure 9 shows the emission spectra from a dye-doped polystyrene sphere with $\sim 80 \mu\text{m}$ diameter under two different pumping intensities. At much lower pumping intensity, which is not shown, the emission spectrum is broad and no remarkable structure is observed. As the pumping intensity is increased, structural spectral lines as shown in Fig. 9 appear. The lasing spectra exhibit a rather simple periodic structure, which may be restricted by a resolution ($\sim 1 \text{ nm}$) of the OMA system. It is found that the mode structure in the lower pumping power above threshold (the lower spectrum) nearly builds up to that in the higher pumping power (the upper spectrum), as it stands. The center wavelengths in these lasing spectra seem to be shifted to the shorter-wavelength region for an apparent lower dye concentration compared to the case shown in Fig. 6.

We examined the size dependence of the DD-WGM laser from the emission spectra. The mode spacing of the observed spectra under the various diameters of the spherical DD-WGM laser is plotted in Fig. 10. The mode spacing is proportional to the inverse diameter of the sphere. This indicates that the present laser operates according to

FIG. 4. Microphotograph of the RH-6G dye-doped spheres, with $\sim 70 \mu\text{m}$ diameter in (a) and fixed on the tip of a needle with $\sim 700 \mu\text{m}$ diameter in (b), respectively.

FIG. 5. Typical oscilloscope trace of a UV N_2 laser pulse measured with a 100 MHz storage oscilloscope. Horizontal scale is 5 ns/div.

FIG. 8. Laser waveforms above threshold in (a) and fluorescence waveform below threshold in (b), measured with a 100 MHz storage oscilloscope under various N_2 laser pumping intensities. Horizontal scale is 5 ns/div.

FIG. 6. Lasing pattern from a DD-WGM laser (the bright-reddish pattern in the central region) in the near field. The yellowish small circle is the spherical DD-WGM laser fixed on the tip of a needle. The horizontally longer beam spot to the left is the fluorescence from the white paper, which is also used for observing a lasing pattern, irradiated by the N_2 laser beam after passing through the DD-WGM laser.

FIG. 9. Emission spectra from the spherical DD-WGM laser with $\sim 80 \mu\text{m}$ diameter under the higher and lower pumping power in the upper and lower curves, respectively, above threshold.

FIG. 7. An appearance of the light emitted in all radial directions from the DD-WGM laser.

FIG. 10. Mode spacing of the observed spectra under the various diameters of the DD-WGM laser. A straight line is obtained for a refractive index of $n=1.6$ for the polystyrene spheres.

the WGM in the spherical cavity. The straight line is obtained from a refractive index where $n=1.6$ for the polystyrene spheres.

IV. DISCUSSION

A homemade open-air TEA UV N₂ laser pumped spherical dye laser has been reported. The RH-6G doped spherical dye laser reported here should provide a simple and inexpensive model system for theory/experiment comparison in the whispering-gallery-mode laser using dielectric small spheres. The present technique may be applied to various experiments such as Raman scattering⁸ and nonlinear optical device engineering,⁹ using small spheres.

ACKNOWLEDGMENTS

The authors would like to express their thanks to Professor H. Inaba of Tohoku Technical University, for his

helpful suggestions. This work was partly supported by the 1991 Grant-in-Aid of the Special Project for Educational Research, in Iwate University.

¹C. G. Garrett, W. Kaiser, and W. L. Bond, *Phys. Rev.* **124**, 1807 (1961).

²H.-M. Tzeng, K. F. Wall, M. B. Long, and R. K. Chang, *Opt. Lett.* **9**, 499 (1984).

³H.-B. Lin, A. L. Huston, B. L. Justus, and A. J. Campillo, *Opt. Lett.* **11**, 614 (1986).

⁴R. E. Benner, P. W. Barber, J. F. Owen, and R. K. Chang, *Phys. Rev. Lett.* **44**, 475 (1980).

⁵M. K. Gonokami, K. Takeda, H. Yasuda, and K. Ema, *Jpn. J. Appl. Phys.* **31**, L99 (1992).

⁶H. Taniguchi and H. Saito, *SPIE* **236**, 294 (1980).

⁷S.-X. Qian, J. B. Snow, H.-M. Tzeng, and R. K. Chang, *Science* **231**, 486 (1986).

⁸J. B. Snow, S.-X. Qian, and R. K. Chang, *Opt. Lett.* **10**, 37 (1985).

⁹S. Sato and H. Inaba, *Electron. Lett.* **28**, 286 (1992).