2023

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## Recommended Citation

Rout, Anuradha; Wang, Zhe; Wang, Zhuochen; and Semenova, Yuliya, "Tunable Erbium-doped Fiber Ring Laser with a Polymer Micro Bottle Resonator" (2023). *Conference Papers*. 6.
https://arrow.tudublin.ie/prccon/6

Funder: Science Foundation Ireland

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# Tunable erbium-doped fiber ring laser with a polymer micro bottle resonator

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## ABSTRACT

A new tunable fiber laser structure based on an erbium-doped fiber ring laser (FRL) and a polymer-based microbottle resonator (PMBR) as the wavelength selective filter is proposed and demonstrated. The tunability of the laser output in response to axial strain of up to 253.6 με applied to the PMBR is demonstrated experimentally. When the strain was applied to the PMBR's long axis, the central lasing wavelength shifted towards shorter wavelengths in a linear fashion. The laser's strain sensitivity was determined to be 0.69 pm/ με. The proposed strain-tunable PMBR laser offers the advantages of simple structure, low cost, robust performance, and has the potential for applications in sensing and tunable micro lasers.

Keywords: Whispering gallery modes, microbottle resonator, tunable laser, polymer, strain sensor

## 1. INTRODUCTION

Whispering gallery mode (WGM) resonators attracted significant research interest in various fields due to their small mode volumes and high-quality factors. For example, in sensing, compared with traditional fiber optic sensors such as fiber Bragg gratings, WGM-based sensors offer higher sensitivity and potentially higher measurement resolution due to their higher Q-factors [1-3]. Light coupled into a dielectric cavity with a circular symmetry, such as a microsphere or a microbottle resonator (MBR) will be confined within the cavity by nearly total internal reflections. In a MBR, light propagates in a spiral fashion reflecting and rotating back to the previous point of incidence. Light then oscillates back and forth between the two turning points, forming an axial mode within a narrow ring near the equator, which is widely used in microlasers and optical sensors [4]. In recent years, many researchers realized the high sensing potential of WGM resonant cavities fabricated from polymer materials. For example, Ioppolo *et al.* demonstrated that microspheres fabricated from Polymethylmethacrylate (PMMA) had higher strain sensitivity than silica microspheres [5-8]. Tuning of WGM lasing modes in a polymer optical fiber (POF) based resonator under tensile strain was reported in [9].

In this work we propose and investigate a new tunable laser structure based on an erbium-doped fiber ring laser (FRL) and a polymer-based microbottle resonator (PMBR) as the wavelength selective filter. The tunability of the laser output in response to axial strain of up to 253.6 με applied to the PMBR is also demonstrated experimentally. When the strain was applied to the PMBR's long axis, the central lasing wavelength shifted towards shorter wavelengths in a linear fashion. The laser's strain sensitivity was determined to be 0.69 pm/με. The proposed strain-tunable PMBR laser offers the advantages of simple structure, low cost, robust performance, and has the potential for applications in sensing and tunable micro lasers.

## 2. SAMPLE PREPARATION AND EXPERIMENTAL SETUP

The PMMA granules (80mg) were directly dissolved in 1400 ml of Methoxybenzene (Anisole). This solution was placed onto a hot stage with a temperature of $50^0$ C for evaporation. The solution was then allowed to fall like droplets across a tapered fiber to create small micro bottles. The final diameter of the PMBRs fabricated using this method was circa 20 μm.

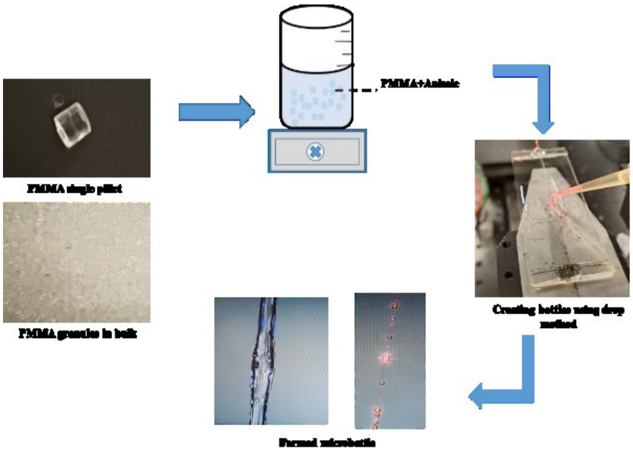

Figure 1. Flow diagram of the fabrication of PMBR on a tapered fiber.

A 980 nm laser diode is employed as a pump laser, with the LD combi controller controlling the power supply. A 13-m-long segment of an erbium-doped fiber absorbs the pump light and generates ASE spectrum in the 1550–1600 nm region. The light emitted from the end of the erbium-doped fiber is then directed to one of the ports (port 3 in the experiment) of a three-port optical fiber circulator (OFC), forming a fiber ring loop. Port 1 of the OC was connected to a thin-tapered fiber (TTF) with PMBR. Light propagating through the fiber taper enters the PMBR and excites a series of WGMs in the axial direction, a portion of it is then reflected back and re-enters the ring cavity via port 2 of the OC. The light transmitted and reflected through the PMBR is highly affected by the MBR shape and absorption within the resonator, therefore the resulting output laser spectrum is tuned when the PMBR is exposed to different strain conditions. The energy transfers from the fundamental mode to the closest few higher order modes depend on the change rate of diameter of the tapered fiber and PMBR. The number of higher-order modes determines the propagation loss. To increase the stability of the system, a polarization controller was created at Port 2 of OFC employing a quarter wave plate-half wave plate-quarter wave plate (QWP-HWP-QWP) system. The output laser spectrum was recorded using an optical spectrum analyzer (OSA) with a spectral resolution of 0.01 nm.

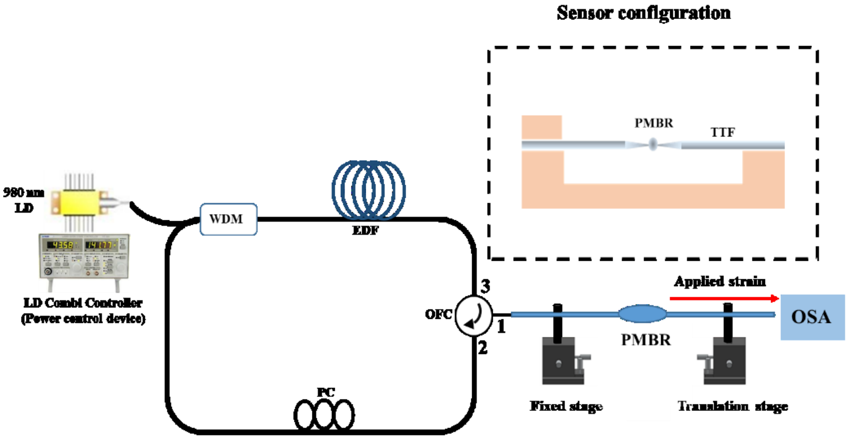

Figure 2. (a) Schematic diagram of the proposed fiber laser for strain sensing. LD: Laser diode, WDM: Wavelength division multiplexer. LD combi controller: Laser diode combi controller. EDF: Erbium-doped fiber, OFC: Optical fiber circulator, TTF: Thin tapered fiber; PC: Polarization controller; PMBR: Polymer micro bottle resonator; OSA: Optical spectrum analyzer;

To apply strain to the PMBR, one end of the taper was immobilized on the glass substrate fixed on a stage and the other end was attached to the second micro translation stage with a resolution of 10 µm, as shown in Fig. 2. The axial length of the PMBR was approximately 13 µm and the total sensing length of the supporting tapered fiber between the fixed points was 30 mm. The strain was applied to the PMBR by moving the translation stage in one directional away from the fixed end with a step of 1 μm (equivalent to an applied tensile strain step of 15.9 με).

The measured output laser spectrum of the proposed structure without applying strain is shown in Fig 3 (a). The peak at 1558.3 nm (10 dB) is observed at pump laser power of 110 mW. The full width at half maximum was measured and the Q factor was calculated using the equation $Q= \lambda/\Delta\lambda$, where $\lambda$ is the wavelength of the laser and $\Delta\lambda$ is the corresponding FWHM. Therefore, FWHM and the corresponding Q-factor at 1558.3 nm were calculated as 3.3 nm and 4 x $10^2$.

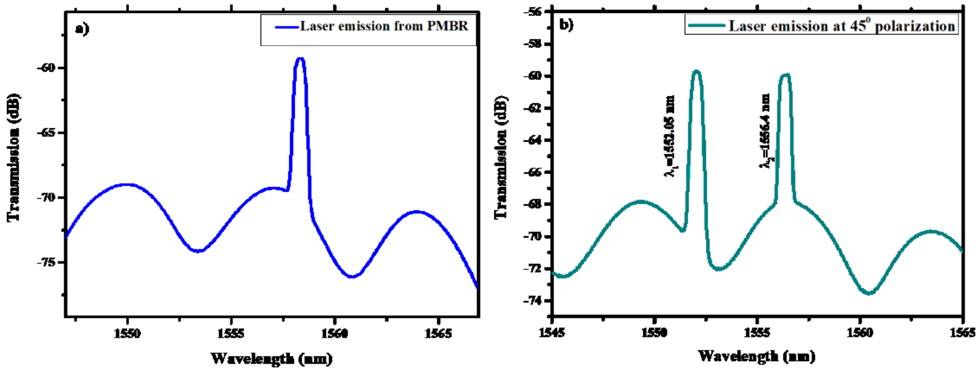

Figure 3. a) The laser output spectrum for the system with a polymer MBR integrated with the FRL. b) The laser output spectra from PMBR with polarization change

In the next experiment the light polarization state within the ring was modified using the polarization controller, while the pump power was fixed at 110 mW. Fig. 3 (b) shows the laser output recorded at $45^0$ polarization state. As can be seen from the graph, two lasing modes were observed at different wavelengths allowing dual wavelength operation. New peaks can be observed at the wavelengths of 1552.05 nm (10.9 dB) and 1556.4 nm (7.7 dB). The FWHM of the above lasing peaks were calculated as 0.71 nm and 1.45 nm respectively.

Finally, laser was stabilized at a central wavelength of 1558.3 nm by changing the paddles of the polarizer. The extinction ratio of the output laser spectrum is 10.2 dB approximately. Fig. 4 (a) shows the laser spectra at different pump laser powers. Eventually, if we keep increasing the power, the height of laser spectra increases. As can be seen from Fig. 4 (b), the system offers a low lasing threshold of 40 mW.

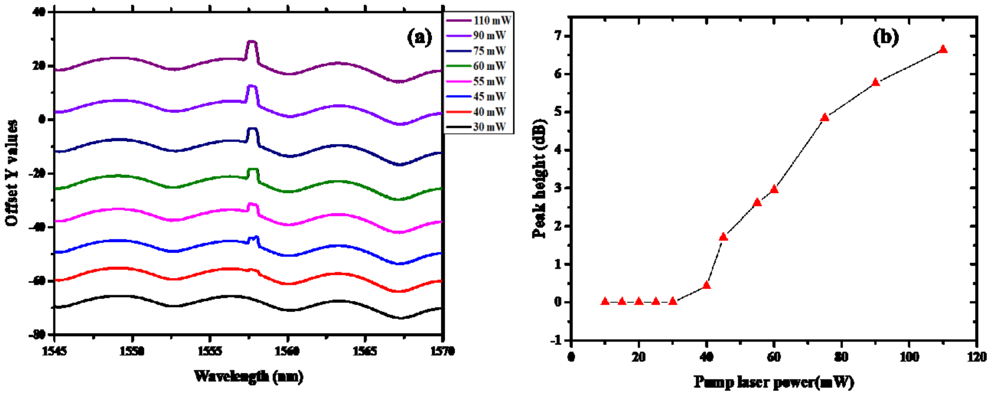

Figure 4. a) Laser emission spectra for different pump laser powers; b) emission intensity at 1558.3 nm as a function of pump laser power.

## 3. STRAIN TUNING EXPERIMENTS

To explore the possibility of tuning the output laser spectrum by applying mechanical strain to the polymer MBR, a series of experiments were carried out by applying axial strain to the micro bottle resonator formed on the tapered fiber in the range from 0 to 253.6 με. In all experiments the power of the pump laser source was kept constant at 110 mW. The entire series of experiments was performed at room temperature 25 $^0$C. Fig. 5 (a) and (b) illustrate the results of the experiments.

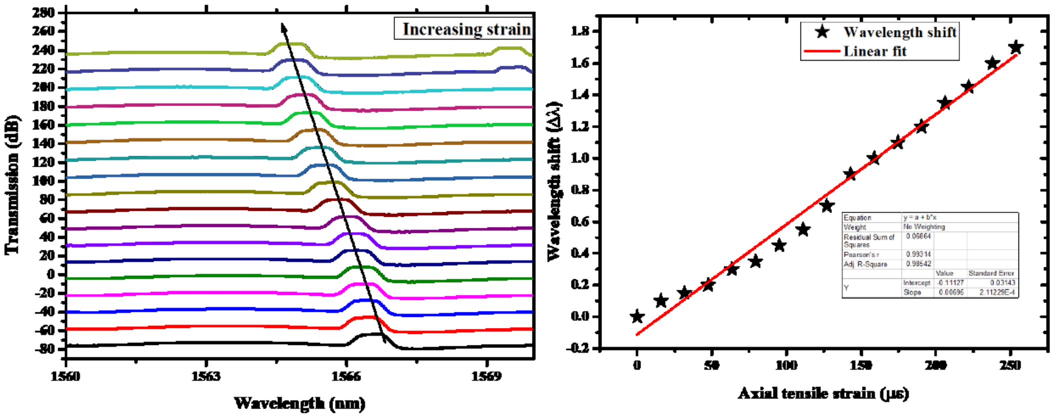

Figure 5. a) Output laser spectra at different values of the applied axial strain; b) central wavelength shift (scatter data) as a function of strain and its linear fit (solid line).

The transmission spectra for the setup with PMBR at different applied axial strain values are shown in Fig. 5 (a). As can be seen from the figure, as the axial strain increases, the laser wavelength exhibits a close to linear blue shift. It could be also seen that the tuning sensitivity of the laser wavelength is circa 0.69 pm/με. For each 1 μm axial elongation (corresponding to a tensile strain of 15.9 με) it is found that the central wavelength shifts by 0.11 nm on average the laser wavelength moves toward shorter wavelengths with the increase of the applied strain. The measured wavelength shift (scatter data) is linearly fitted (solid line) as depicted from Fig 5 (b). Linear fitting of the wavelength response data indicates that the linear regression coefficient is greater than 0.99. The slope of the linear dependency is 0.69 pm/με.

## 4. CONCLUSION

A simple and low-cost technique was developed to fabricate polymer optical WGM microresonators with a bottle-like shape. The WGMs in such a microbottle can be excited through the fiber taper that serves as the support for the MBR with Q-factors in the order of $10^3$. A novel laser structure based on a combination of FRL and a polymer MBR has been demonstrated and its responses to axial strain have been studied. The spectral position of the central lasing wavelength moved linearly towards shorter wavelengths when mechanical strain was applied to the polymer MBR long axis in the range from 0 to 253.6 με. The strain sensitivity of the system was calculated as 0.69 pm/ με.

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