Journal of Luminescence 149 (2014) 204–207

Contents lists available at ScienceDirect

Journal of Luminescence

journal homepage: www.elsevier.com/locate/jlumin

Multimode laser emission from free-standing cylindrical microcavities

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ARTICLE INFO

Article history:
Received 31 October 2013
Received in revised form
31 December 2013
Accepted 2 January 2014
Available online 15 January 2014

Keywords:
Cylindrical microcavity
Q-value
Red-shift
FWHM

ABSTRACT

We report a well resolved whispering gallery mode (WGM) laser emission from a free-standing microring cavity based on a dye doped hollow polymer optical fiber (DDHPOF), which is transversely pumped by a pulsed Nd:YAG laser. The microring laser is characterized by a well-defined, low threshold pump power at which the emission spectral intensity dramatically increases and collapses into several dominant microcavity laser modes with reduced mode spacing and high *Q*-value. Resonant modes are excited inside the gain medium which is strongly confined along the radial direction so that the spacing of lasing modes is controlled by the diameter of the cylindrical microcavity. A variation in the free spectral range of WGM spectra from 0.23 to 0.09 nm coupled with a red-shift is observed with an increase in the diameter of DDHPOFs.

1. Introduction

There has been a growing interest in exploiting organic and polymeric materials as they can be made to provide high optical gain and good stimulated emission properties for various laser applications [1]. Wide tunability and high efficiency of laser dyes coupled with the high power density that can be easily achieved in waveguide structures make the devices based on dye doped polymer waveguides and fibers very promising [2]. Microring laser cavity offers a low resonance structure that has been utilized to demonstrate lasing with organic gain media [3]. Over the past several years, optically pumped microring laser emissions have been observed from different polymer gain materials. Cylindrical polymer microcavity provides excellent coupling of spontaneous emission into lasing modes and a high cavity *Q*-value which consequently leads to low lasing thresholds [4,5]. Due to their high *Q*-value and small mode volume, which leads to unprecedented narrow linewidth, these resonators are used in microlasers, biosensing applications [6,7], optical switches, add or drop filters [8,9], etc. This technique may be applicable to a wide range of material systems because low optical cavity loss is obtained from a simple curved surface instead of multiple layer dielectric mirrors [10].

A micron sized polymer waveguide can confine light to its interior volume. The trapped light describes an orbital trajectory circum-navigation just below the cylindrical waveguide surface. The light in such cavities is practically confined inside the gain medium by lossless total internal reflections [3]. The loss is due to the cavity surface curvature and light scattering from imperfections. When the waves come in-phase at a point after every roundtrip, constructive interference takes place. Resonance occurs when the guided wave drives itself coherently by returning in-phase after every revolution, thereby requiring an integer number of waves in one circum-navigation. The wave nature of the light allows the photon to penetrate beyond the dielectric boundary and into the surroundings as an evanescent field as occurs in Goos–Haschen shift in case of optical fibers. Whispering gallery resonators have a size-dependent resonant frequency spectrum [11]. Resonators with diameters from a few tens to several hundreds of micrometers can have a very large free spectral range of several nanometers. Laser emission from these microcavities of dye doped fibers has been reported from hollow [10], step index [12] and graded index [13] optical fibers.

Given the low threshold lasing characteristics of microcavity lasers, their relatively simple formation from polymers and their ability to be integrated directly into other optical components offer good opportunities for their commercial applications [14]. Laser dye doped poly (methyl methacrylate) is found to be a highly efficient gain medium for laser source with narrow pulse width, wide tunable range as well as high gain, high power conversion and broad spectral bandwidth for optical amplifier [10]. Furthermore, theoretical studies have been reported on the resonance modes in a concentric or eccentric ring-type cavity [15]. Experimental studies on the ring-type cavity were also reported but not widely due to the difficulty in the fabrication and realization of ring-type cavity systems [16]. An amplified spontaneous emission (ASE) and the outset of multimode laser emission from a doped hollow fiber have been reported by Kailasnath et al. [10] but

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0022-2313/$ - see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jlumin.2014.01.003

a detailed study of the evolution of the modes has not been done so far. Also in their studies, the excitation of the fiber was done through side illumination and the collection was axial. In this paper we report the multimode laser emission characteristics at room temperature from different diameter hollow cylindrical microcavities made up of rhodamine 6 G (10^{-4} mol/l) doped hollow poly (methyl methacrylate) (PMMA) and optical fibers pumped by a frequency doubled Q-switched Nd:YAG laser.

2. Experimental

The typical procedure for the fabrication of dye-doped hollow polymer optical fiber (DDHPOF) was already furnished by Kailasnath et al. [10]. A variety of microrings with different outer (OD) and inner (ID) diameters, such as 310 and 160, 400 and 210, 550 and 280 and 660 and 340 μm, respectively, were fabricated by utilizing the same technique from the same preform tube. The variation in the OD measured for the different DDHPOFs is around 2 μm. In our case, the d/D ratio for the different diameter DDHPOF is ~0.25. In the experimental setup, the DDHPOF is transversely pumped at 532 nm with a frequency doubled Q-switched Nd:YAG laser (Spectra Physics) with 8 ns pulses at 10 Hz repetition rate as shown in Fig. 1. A set of calibrated neutral density filters was used to vary the pump power. The pump beam was focused onto the sample with the help of a convex lens of focal length 75 mm. The laser emission in the radial direction from the cylindrical microcavity was collected using a collecting fiber. The laser emission was directed to a spectrograph (SpectraPro-500i) coupled with a cooled CCD array with a resolution of 0.03 nm.

In a thicker microring cavity ($d/D \geq 0.2$), where D is the outer diameter of micro-cavity and d is the thickness of ring (dye doped region), resonant modes are no longer waveguided [17]. In fact these optical modes never reach the inner /outer interface and, therefore, are dubbed whispering gallery modes (WGMs) [4,18]. The light in this case is confined by total internal reflections at the interface between air and dye doped region, and the mode intensity distribution is concentrated on the outer edge of the fiber and hence it can be easily collected from outer surface area of due doped hollow polymer optical fibers (DDHPOFs). The hollow fiber acts as a waveguide forming a ring resonator similar to a polymer film on an optical fiber. An optical resonance will occur when the optical path length traveling inside the resonator is an integer multiple of wavelength. Here the path length is the circumference of the fiber. So WGM frequencies in an optical fiber, or indeed any cylindrical resonator, are reasonably well approximated by matching an integral number of wavelengths to the resonator circumference, i.e.

$$m\lambda_m = \pi D n_{eff} \quad (1)$$

where m is an integer, λ_m is the free space wavelength, n_{eff} is the effective refractive index of the resonator and D is the resonator diameter.

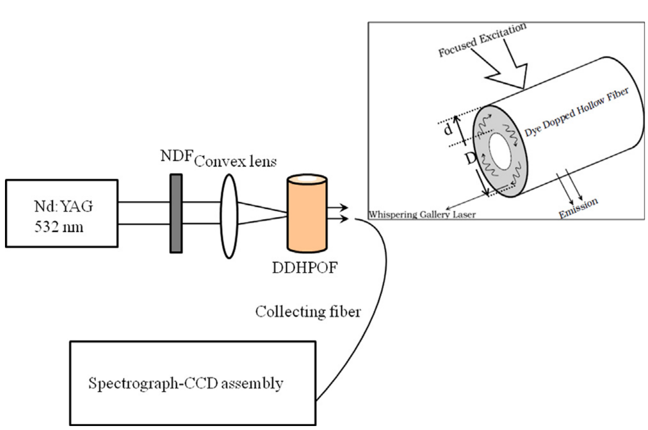

Fig. 1. Schematic illustration of experimental setup. Inset shows zoomed version of WGM laser emission from DDHPOF under pulsed excitation.

3. Results and discussions

At low pump intensities, the emission spectrum from 400 μm DDHPOF exhibited a broad luminescence with a peak at 565 nm. By increasing the pump power we observed an increase in the

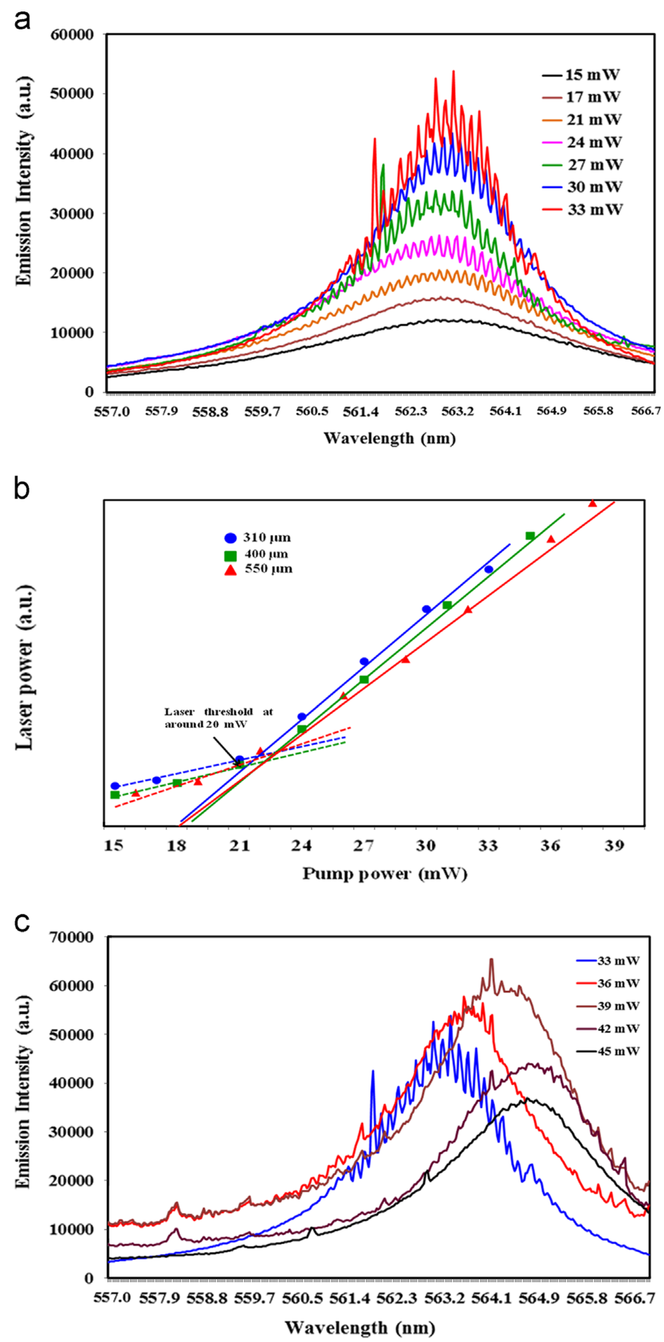

Fig. 2. (a) The emission spectra from 400 μm diameter DDHPOF at different pump powers. (b) The output laser versus the pump power for different diameter DDHPOFs. The linear dependence and change in slope reveal laser action. The lasing threshold is at about 20 mW. (c) The emission spectra from 400 micron diameter of DDHPOF after bleaching of the dye.