Self-Locked Excitation Scheme for Microsphere Resonators

Khanh Kieu and Masud Mansuripur

***Abstract*—We propose a new scheme for exciting a resonant mode of a glass microsphere resonator. The concept is based on unique properties of coupled resonators. In the proposed setup, the microsphere plays the role of a feedback mirror in an erbium-doped fiber laser, where the lasing wavelength is automatically locked to a resonant mode of the microsphere. As a result, the laser radiation builds up to very high intensities inside the microsphere. Using a (multimode) pump diode laser at relatively low pump power, we achieve continuous-wave stimulated Raman lasing and generation of new laser frequencies by four-wave mixing.**

***Index Terms*—Fiber laser, microsphere resonator, whispering gallery modes (WGMs).**

I. INTRODUCTION

MICROSPHERE resonators are of interest for a variety of applications such as compact, low-threshold lasers [1] and high-sensitivity bio-sensors [2]. These resonators exhibit the so-called whispering gallery modes (WGMs), which normally possess ultrahigh quality factors ($Q \sim 10^8$) [3]. The strong resonant build-up of optical energy inside these cavities allows nonlinear optical effects to occur at relatively low pump powers [4], [5]. Dielectric microsphere resonators are also interesting for studies of quantum electrodynamics [6].

In existing publications, authors have typically required a tunable single-frequency narrow linewidth laser to effectively excite a particular WGM of a microsphere resonator. This type of microcavity is normally associated with an ultrahigh Q-factor, which produces an extremely narrow resonance linewidth (less than a few megahertz). Since a laser's wavelength typically drifts in time (at best in the megahertz range), it is difficult in practice to lock a tunable laser's wavelength to a resonance mode of the microspherical cavity without the use of an active locking technique [7]. The present letter proposes a new scheme to lock the lasing wavelength of an Er-doped fiber laser to a resonance mode of a microspherical cavity. The locking is self-tracking and does not require expensive/complex control equipment. We believe this technique renders many of the applications of microspherical resonators (e.g., Raman lasers [4], [5]) practical.

WGMs supported by structures such as microspheres, microrings, and microtoroids have been exhaustively studied in the literature [8]. Normally, each WGM of a microsphere resonator is characterized by three mode numbers plus a polarization state; these include a radial mode number n (which represents the number of maxima of the optical field in the radial direction), an angular mode number ℓ (which represents the number of maxima of the optical field around the circumference of the resonator), and an azimuthal mode number m (which matches the number of lobes around the equatorial circle). Modes with the lowest radial number ($n = 1$)—generally confined to the vicinity of the microsphere surface—possess the highest Q-factor. The spectrum of WGMs in a dielectric microsphere is quasi-periodic, with a free spectral range (FSR) defined by a change of the angular mode number ℓ by one unit. In practice, due to the nonideal circular shape of the microsphere, the corresponding WGM spectra are rich in detail, as the degeneracy of modes having different azimuthal mode numbers m is lifted [9].

II. EXPERIMENTAL SETUP AND MEASUREMENT RESULTS

Our microspheres are made by heating fiber tips (made by heating and pulling apart a standard single-mode fiber) using a pair of electrodes in a fiber fusion splicer. This technique yields high-quality microspheres ranging in diameter from ~10 to ~500 μm. An adiabatic fiber taper is then used to couple the light into and out of these microspheres [10]. The gap distance between the microsphere and the taper is controlled with submicron precision using a piezoelectric-actuator. To observe the WGMs of a given microsphere, we use a narrow-linewidth tunable laser (Agilent 81682A, linewidth $>$ 100 kHz). Varying the wavelength around $\lambda = 1550$ nm, we record the transmission and/or reflection of the laser light from the microsphere. Fig. 1 shows the recorded resonant structure of a WGM of a microsphere. WGMs appear as dips in the transmission curve, and also as peaks in the reflection curve. It is well known [11] that each resonant mode of a microsphere splits into two due to coupling between clockwise and counterclockwise propagating beams (e.g., coupled resonators); see Fig. 1. This occurs when the light launched in the clockwise direction is partially backscattered in the counterclockwise direction, and vice-versa. The fiber taper serves not only as a means of coupling the light into a resonant mode of the microsphere, but also as a means of extracting the light out of the cavity (and launching it back into the fiber). This explains the appearance of backward-propagating light within the fiber where the initial propagation direction was forward only. Depending on the gap distance between the microsphere and the taper, reflectivities as high as 80% were observed. Using this effect, we have demonstrated that the microsphere can be used as a feedback mirror in a fiber laser [12].

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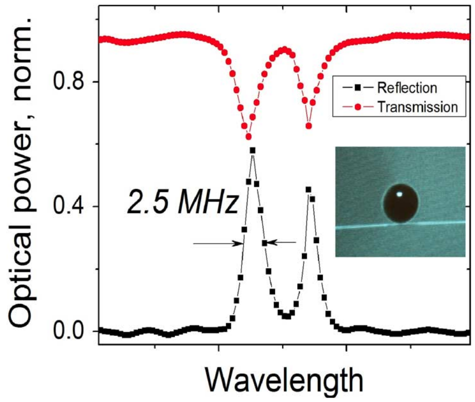

Fig. 1. Doublet resonance structure of a WGM. Inset: photograph of the microsphere-taper system; the taper (diameter ~2 μm) is visible as a white line below the microsphere (diameter ~ 55 μm).

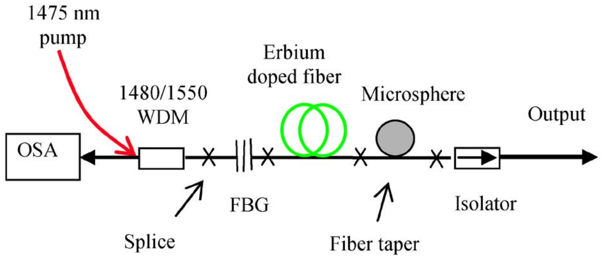

Fig. 2. Diagram of an Er-doped fiber laser with a microsphere used as a reflector. The lasing wavelength is automatically locked to one of the microsphere's modes.

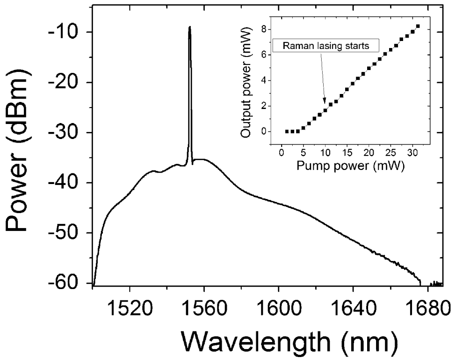

Fig. 3. Fiber laser's emission spectrum at $P_{\rm pump} = 6$ mW. Inset: dependence of the laser output power on the pump power. Stimulated Raman lasing starts at $P_{\rm pump} \sim 10$ mW.

Intuitively, it is obvious that this approach can also be used to resonantly couple light into one of the WGMs of the microsphere, thus eliminating the need for a single-frequency, narrow-linewidth, tunable laser, and complicated locking schemes.

To estimate the Q-factor of our microspheres, we analyzed a single resonance within the WGM spectrum in the under-coupled regime [13]; see Fig. 1. The laser power was kept low, ~10 μW, to avoid thermal modification of the resonance linewidth, which, from this data, is estimated at ~2.5 MHz, corresponding to $Q \sim 0.77 \times 10^8$. (Note also the resolving of the doublet, which is produced by the coupling between clockwise and counterclockwise propagating modes.)

The self-locking excitation scheme is shown in Fig. 2. The fiber laser is pumped by a fiber-pigtailed diode laser operating at $\lambda = 1475$ nm. For the active medium, we use ~6 m of standard Er-doped fiber (~5-dB absorption at $\lambda \sim 1475$ nm). One mirror of the laser cavity is a fiber Bragg grating (FBG) having 99.3% reflectivity centered at $\lambda \sim 1553.2$ nm (full-width at half-maximum bandwidth ~1.16 nm). The other mirror is formed by a silica microsphere resonator, ~55 μm in diameter, coupled to the fiber laser via a fiber taper, as shown in the inset in Fig. 1; (taper diameter ~1–2 μm; loss ~15% around $\lambda = 1550$ nm). The gap distance between the microsphere and the taper is controlled with submicrometer precision using a piezoelectric-actuator. A fiber-optic isolator is inserted after the fiber taper (see Fig. 2) to avoid feedback into the laser cavity from parasitic reflections. The laser emission spectrum from one end of the cavity is analyzed using an optical spectrum analyzer (OSA). Output power is measured using a power-meter from the other end of the laser cavity.

At any pump power, when the gap between the fiber taper and the microsphere is large, we do not observe any sign of lasing in the emission spectrum (as measured by the OSA). When the gap is reduced to below ~2 μm, a sharp laser line appears around 1553.2 nm, the reflection wavelength of the FBG; see Fig. 3. The dependence of the laser output power on the pump power is shown in the inset to Fig. 3. Due to the low loss of our laser cavity, a pump threshold of less than 3 mW is obtained. The output power stays linearly dependent on the pump power up to the highest $P_{\rm pump} \sim 120$ mW.

At $P_{\rm pump} > 10$ mW, emission lines around $\lambda \sim 1667$ nm begin to appear in the output spectrum. We attribute this emission to stimulated Raman lasing inside the microsphere resonator. The construction of our laser requires that lasing inside the Er-doped fiber occur at a wavelength that matches not only the high-reflectivity wavelength of the FBG, but also that of a resonant mode of the microsphere. This is why the high-Q microsphere is automatically pumped (on-resonance) by the laser radiation, which provides the condition for intensity build-up within the microspherical cavity. The final result of all these effects is stimulated Raman lasing inside the microsphere. (We mention in passing that stimulated Raman lasing was shown previously [4] to occur in similar microspheres at low pump powers, i.e., below 100 μW, but not in a controlled continuous-wave fashion, as is the case in the present work.) The fact that our laser output stays linearly dependent on the pump power (even after Raman lasing has begun) is an indication that the Raman conversion efficiency is high and, possibly, that radiation at 1550 nm was coupled back into the fiber before it could be significantly depleted by the Raman effect. The onset of stimulated Raman lasing at relatively low pump power in our system suggests that the optical field inside the microspherical cavity is built up to sufficiently high levels, thus proving the utility of our self-locking concept for the lasing wavelength.

Fig. 4 shows the emission spectrum of our laser at $P_{\rm pump} \sim 70$ mW. When the microsphere is resonantly pumped, stimulated Raman lasing occurs and, due to the large bandwidth of the Raman gain in silica glass, multiple Raman lines—separated by the FSR of the microsphere—are observed. Our microsphere has a diameter of ~55 μm, which corresponds to

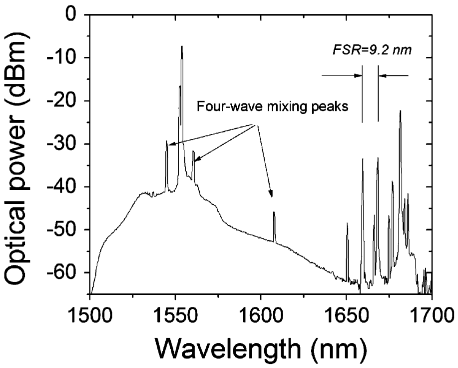

Fig. 4. Fiber laser's emission spectrum, obtained at a relatively high pump power (∼70 mW). The microsphere diameter in this system is ∼55 μm.

the ∼9-nm FSR seen in Fig. 4. In addition to the (nonlinear) stimulated Raman lasing, we observe four-wave-mixing (FWM) peaks (generation of up- and down-shifted frequencies around 1553 nm). The observed FWM shifts in Fig. 4 around $\lambda \sim 1553$ nm match the FSR of the microsphere resonator. The presence of FWM peaks in the output spectrum indicates a very high optical field has built up inside the microsphere resonator. This effect also then confirms the self-locking mechanism of the Er-laser wavelength into one of the resonance modes of the microsphere resonator.

III. CONCLUSION

We have proposed and demonstrated a scheme for excitation of a WGM in a microsphere resonator. The lasing wavelength of an Er-doped fiber laser is automatically locked to one of the WGMs of the microsphere; the lock being self-tracking, it does not require expensive and complex equipment for its control. We believe this technique would make many of the applications of microsphere resonators (e.g., Raman lasers [4], [5]) practical. The proposed technique should be equally applicable to other types of resonator, such as microrings and microtoroids, that support WGMs as well.

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