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# Miniaturized Optical Microwave Source Using a Dual-Wavelength Whispering Gallery Mode Laser

Lei Xiao, Stéphane Trebaol, Yannick Dumeige, Zhiping Cai, Michel Mortier, and Patrice Féron

**Abstract**—We report on the observation of a compact optical microwave source based on a whispering gallery mode (WGM) laser. The use of a single 160- $\mu\text{m}$  diameter erbium-doped glass microsphere and two half fiber tapers allows a dual single-mode laser emission around 1550 nm to be obtained. The generated beat note at 10.86 GHz has a linewidth of 22 kHz. This preliminary experimental demonstration shows the potentialities of erbium-doped WGM resonators for microwave generation.

**Index Terms**—Lasers, microresonators, microwave generation.

A LOW phase noise microwave signal is required for many applications such as in radar, long-range transmission of millimeter-waves, or instrumentation. The distribution of microwave signals is strongly limited due to the high losses of electrical lines [1]. The broad bandwidth and very low loss optical fiber systems can be used to circumvent this issue. In this context, the generation of optically carried microwaves is of great interest. One of the generation techniques consists of the heterodyning of two optical waves [1], [2]. In particular, two semiconductor lasers can be used to obtain an integrated optical microwave generator. However, their intrinsic properties such as broad linewidth or strong intensity noise impose severe constraints on their frequency stabilization procedure [3]. Rare-earth lasers are good candidates for the implementation of the usual technique of stabilization due to their low-noise feature [2]. Even though some efforts have been made to greatly increase their compactness, most dual-wavelength rare-earth lasers have typical dimensions larger than semiconductor devices. Rare-earth-doped microspheres are tiny lasers which intrinsically offer narrow linewidth emission [4]. From another point of view, it has already been demonstrated that a nonlinear whispering gallery mode (WGM) resonator can be used to obtain a narrow linewidth integrated microwave source based on hyper-parametric oscillations [5]. The beating of two WGM single-mode lasers can be used to obtain a

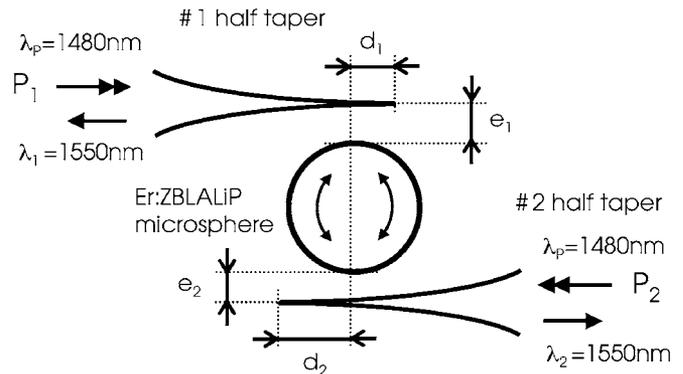


Fig. 1. Schematic sketch showing the WGM microsphere and the two half fiber tapers.  $d_i$  and  $e_i$  are, respectively, the position of the taper with respect to the sphere and the gap between the sphere and the taper. The tapers allow the pump laser (wavelength  $\lambda_p$ ) to be coupled inside the sphere and the laser signals (wavelength  $\lambda_1$  and  $\lambda_2$ ) to be extracted.  $P_1$  and  $P_2$  are the pump power injected in the tapers.

narrow linewidth microwave signal. In this letter, we propose a compact dual-wavelength rare-earth WGM laser generating microwaves at 10.86 GHz with a 22-kHz linewidth in a free running configuration.

Our system is composed of a single  $\text{Er}^{3+}$ -doped glass microsphere pumped using two half fiber tapers as shown in Fig. 1. Since the two tapers are not exactly located in the same equatorial plane, they do not couple pump or signal to the same WGM. Consequently, we can obtain two different lasers sharing the same cavity without mode competition as it is the case for spatially separated eigenstates configuration demonstrated in [6]. This property is important since it should insure that first-order frequency fluctuations between the two lasers cancel. The microsphere is made of ZBLALiP ( $\text{ZrF}_4\text{-BaF}_2\text{-LaF}_3\text{-AlF}_3\text{-LiF-PbF}_2$ ) fluoride glass doped with  $\text{Er}^{3+}$  ions. A study of some fundamental material properties of this glass was reported previously. The improved stability of  $\text{Er}^{3+}$ :ZBLALiP with respect to similar fluorozirconate glasses and its suitability as host matrix for rare-earth ions have been already discussed [7]. This type of glass is well adapted to the development of the microspherical laser operating in the infrared region; in particular, it gives a laser emission ranging from 1530 to 1570 nm. The spheres were obtained by fusion of glass powders using a microwave plasma torch as already reported in [4]. The diameter  $D$  of the free spheres fabricated using this method depends essentially on the powder size and varies from 10 to 200  $\mu\text{m}$ . The selected sphere is glued at the tip of an optical fiber (typically drawn to 20  $\mu\text{m}$  in diameter) which allows the optical setup to be easily manipulated. The results presented in this letter have

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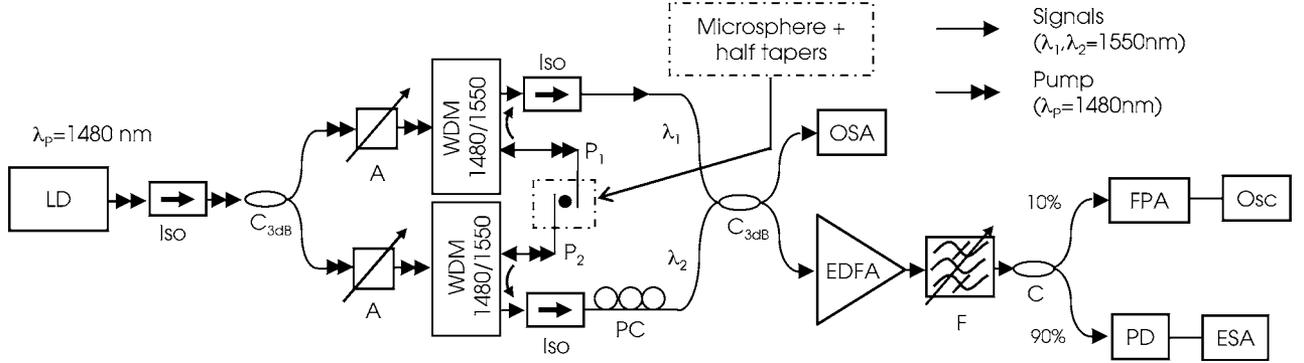


Fig. 2. Experimental setup. LD is the pump LD ( $\lambda_P = 1480$  nm). Iso are optical isolators,  $C_{3\text{dB}}$  are 3-dB couplers, and  $A$  are two tunable attenuators. WDM are wavelength multiplexers allowing the pump light to be inserted and the laser signals to be extracted. PC is a polarization controller. The mixed signal is analyzed using an OSA and a 40-dB EDFA.  $F$  is a tunable filter.  $C$  is a 90%/10% coupler. PD is a 15-GHz-bandwidth PD which is connected to an electrical spectrum analyzer (ESA). We also use a confocal FPA and an oscilloscope (Osc) to monitor the optical spectrum. The PD can be replaced by a delayed self-heterodyne detection setup to accurately analyze the laser lines.

been obtained using a 0.1-mol% erbium-doped ZBLALiP microsphere with a diameter  $D = 160 \mu\text{m}$ . The refractive index of ZBLALiP around  $\lambda = 1550$  nm is approximately  $N = 1.5$ . The sphere ellipticity is around  $e = 1\%$ . The WGM of the microsphere are described by their polarization [transverse electric (TE) or transverse magnetic (TM)] and three quantum numbers  $(n, \ell, m)$  which represent the radial, angular, and azimuthal mode numbers, respectively. Taking into account the characteristics of the microsphere, we find for a fixed  $n$ -number a mode spacing or pseudo-free spectral range  $\text{FSR} = c/(\pi ND) \approx 400$  GHz [8]. Due to the residual ellipticity of the sphere, the mode degeneracy for different values of  $m$  is removed. Assuming that  $\ell \gg \ell - |m|$ , the minimal mode separation is  $\text{FSR} \times e \approx 4.0$  GHz [9]. Finally, the spacing between TE and TM modes is  $\text{FSR} \times \sqrt{N^2 - 1}/N \approx 300$  GHz [8]. For each of the half tapered fibers, the gap ( $e_i$  with  $i \in \{1, 2\}$ ) and the position ( $d_i$ ) between the half-taper and the sphere were controlled by a three-axis micro-translation stage (Fig. 1). The first (numbered as #1 half taper) is characterized by a drawn length of  $L = 198 \mu\text{m}$  and a taper end reduced to  $\phi = 2.8 \mu\text{m}$  in diameter. The second (#2 half taper) is characterized by  $L = 195 \mu\text{m}$  and  $\phi = 2.8 \mu\text{m}$ . For a given position of the taper and thus a local taper diameter, the matching between the effective refractive index of the guided mode of the taper and that of the high quality factor WGM depends on the wavelength [10]. As the half taper is less selective than a prism coupling system, it excites more  $(n, \ell, m)$  modes, which leads to complex WGM spectra as previously described [4]. Consequently, this kind of coupler allows the emitted wavelength to be selected among all these modes and each taper can be considered as a wavelength tunable input/output coupler by varying the position  $d_i$  and the gap  $e_i$  between the sphere and the taper. For example, for fixed pumping rate and position  $d_i$ , it is possible to tune the laser emission over 10 GHz. Note that the thermal effect could also be used to obtain a simultaneous tunability of the lasers over 100 GHz [11]. Fig. 2 shows the schematic diagram of our experimental setup. The laser pumping source consists of a laser diode (LD). We used  $\lambda_P = 1480$  nm as pump laser wavelength in order to obtain a good overlap between the pump and laser WGM volumes. The use of two closed pump and

signal wavelengths is also favorable for improving the coupling of the pump light from a tapered fiber while preserving efficient collection of the laser output signals into the same fiber. An optical isolator (Iso) is used to prevent feedback into the LD pump. In order to independently pump the two microspheres by the two different half tapers, we use a 3-dB coupler to divide the pump source in two balanced channels. Each coupler output is connected to a variable attenuator ( $A$ ) and a 1480/1550-nm wavelength-division multiplexer (WDM). The WDM is used to pump the sphere and to collect the signal (fluorescence or laser) while filtering the residual counterpropagating pump. The two signals collected via the half tapers are mixed using a 3-dB coupler. A fraction of the hybrid signal allows the double wavelength WGM laser to be monitored by a 0.07-nm resolution optical spectrum analyzer (OSA). The second output of the coupler is used to obtain the microwave signal. Before detection, the signal is amplified using an erbium-doped fiber amplifier (EDFA) and filtered by a 3.4-nm bandwidth tunable filter  $F$ . This filter is used to partially reject the amplified spontaneous emission generated in the EDFA. Finally, 90% of the signal is sent to a fast photodiode (PD) and the beating of the two lasers at  $\lambda_1$  and  $\lambda_2$  is analyzed using an electrical spectrum analyzer with a resolution of 300 Hz. The polarizer controller (PC) is used to optimize the beat note amplitude. The second output of coupler  $C$  is analysed using a confocal Fabry-Pérot analyzer (FPA) whose FSR is around 10 GHz connected to an oscilloscope (Osc). This last measure allows the optical spectrum of the signal sent to the fast PD to be measured with a resolution of 50 MHz.

To obtain the beating of only two frequencies at the fast PD, we have to collect two single-mode laser emissions with the two half tapers. We proceed as follows: 1) we measure independently (thanks to the tunable attenuators) the laser spectra of outputs #1 and #2 using the OSA; 2) we choose two pump powers (here  $P_1 = 3.2$  mW and  $P_2 = 4.0$  mW) to insure apparent single-mode operation of the two lasers and to maximize the laser outputs which are estimated around 500 nW. We recall that the OSA resolution is 8.75 GHz. At this point, we observe two single-mode laser emissions strongly spectrally separated. To obtain a beat note in the microwave domain, we tune the two

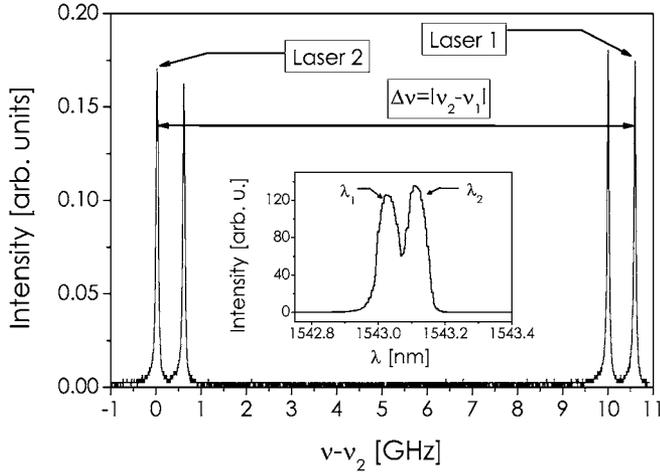


Fig. 3. Optical spectrum obtained using the FPA. The abscissa has been converted into frequency units assuming that the FSR of the FPA is 10 GHz.  $\nu$  is the frequency. We obtain a sequence of two peaks corresponding to the two laser frequencies  $\nu_1$  and  $\nu_2$ . The inset is the spectrum obtained with the OSA:  $\lambda_1 = 1543.05$  nm and  $\lambda_2 = 1543.15$  nm.

lasers by changing the relative positions ( $d_i$  and  $e_i$ ) of the tapers with respect to the sphere. We can obtain a spectral interval  $\Delta\nu = |\nu_2 - \nu_1|$  reduced to few gigahertz, as shown in the inset of Fig. 3, which represents the spectrum obtained with the OSA ( $|\lambda_2 - \lambda_1| \approx 0.1$  nm which corresponds to about 12.5 GHz at  $1.55 \mu\text{m}$ ). The two peaks are not resolved due to the OSA resolution. Due to the weak spectral selectivity of the half tapers, it could be possible to obtain laser emissions separated by only 4.0 GHz because of the ellipticity of the sphere. Thus, before the electrical analysis of the beat note signal, we check that we have only two wavelengths using the FPA which has a much better resolution than the OSA. The corresponding spectrum is given in Fig. 3. In one FSR of the FPA, we observe two peaks separated by about 1 GHz which shows that the two laser emissions are single-mode. Using the OSA and FPA spectra, we can conclude that the spectral separation between the two laser frequencies is around 11 GHz rather than 1 GHz (Fig. 3). Fig. 4 shows the beating signal of the two laser radiations at the PD output. The observation of a single line further confirms that the dual laser is single-mode. The central frequency is around 10.86 GHz in good agreement with the optical spectrum measured using the FPA. In order to estimate the stability of the source, we monitored the microwave signal during 30 min with a time interval of 2 min. The microwave frequency drift is less than 300 kHz and the fluctuation of the microwave signal power is around 1 dB. The inset of Fig. 4 shows a detailed spectral analysis of the beat note whose central frequency has been shifted to zero for convenience. The full-width at half-maximum (FWHM) of the microwave signal is 22 kHz which corresponds to the sum of the FWHM of the two single-mode lasers [12]. This value is of the same order of magnitude as those obtained using free running dual-wavelength fiber lasers [1].

We have observed the generation of a narrow linewidth microwave signal at 10.86 GHz using a dual-wavelength single-mode WGM free running laser. The tunability of the two lasers

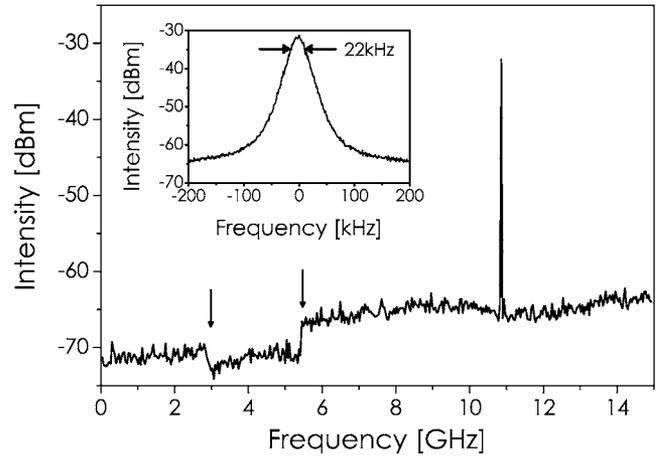


Fig. 4. Microwave signal generated by the beat note of the two single-mode lasers at the fast PD output. The microwave frequency corresponds to the difference between the two laser frequency. Arrows give the two analyzer sensitivity changes. The inset represents an high resolution measurement of the linewidth.

could allow microwave, whose frequencies would be only limited by the bandwidth and the sensitivity of the PD, to be generated. This experimental result is a first step toward a really compact rare-earth-based tunable microwave source. Further works will be devoted to the study of microwave frequency tunability and phase noise measurements.

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