

Self-locked orthogonal polarized dual comb in a microresonator

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Dual combs are an emerging tool to obtain unprecedented resolution, high sensitivity, ultrahigh accuracy, broad bandwidth, and ultrafast data updating rate in the fields of molecular spectroscopy, optical metrology, as well as optical frequency synthesis. The recent progress in chip-based microcombs has promoted the on-chip dual-comb measuring systems to a new phase attributed to the large frequency spacing and broad spectrum. In this paper, we demonstrate proof-of-concept dual-comb generation with orthogonal polarization in a single microresonator through pumping both the transverse-electric (TE) and transverse-magnetic (TM) modes simultaneously. The two orthogonal polarized pumps are self-oscillating in a fiber ring cavity. The generated dual comb exhibits excellent stability due to the intrinsic feedback mechanism of the self-locked scheme. The repetition rate of the two orthogonal combs is slightly different because of the mode spacing difference between the TE and TM modes. Such orthogonal polarized dual-combs could be a new comb source for out-of-lab applications in the fields of integrated spectroscopy, ranging measurement, optical frequency synthesis, and microwave comb generation. © 2018 Chinese Laser Press

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1. INTRODUCTION

Optical frequency combs (OFCs) are referred to as optical rulers where the spectra possess a precise sequence of discrete and equally spaced frequency lines. OFCs directly link microwave and optical frequencies [1] and have revolutionized the fields of optical metrology [2], spectroscopy [3], optical frequency synthesis [4], etc. The recently developed dual-comb spectroscopy (DCS) could especially provide previously unattainable high precision, sensitivity, and measurement speed even compared with the state-of-the-art Fourier-transform spectrometers (FTSs) [5–9]. For optical ranging measurement, a dual-comb scheme has achieved sub-micrometer (μm) precision with the highest measuring rate, which exceeds the fastest previous reported systems by more than one order of magnitude [10–12]. The principle of a dual-comb measurement system can be analogous to a sampling oscilloscope [13]. One OFC with a repetition rate of f used as signal is sampled by another OFC

with a repetition rate of $f + \Delta f$ ($\Delta f \ll f$). To avoid the converted radio frequency (RF) spectrum overlap, the bandwidth of the dual-comb should satisfy $\Delta\nu \leq f^2/(2\Delta f)$. The effective sampling interval is about $\Delta f/f^2$, and the minimum acquisition time is simplified to $1/\Delta f$ [13]. So dual-comb sources with a higher repetition rate could be helpful for increasing the measurement resolution while keeping the acquisition speed. Mode-locked-laser based dual-combs have been extensively employed in DCS [6,14], but the low repetition rate (generally less than 1 GHz) limits the applications with fast dynamic processes, such as the broadband absorption features of liquids or solids [13]. Fortunately, the repetition rate of microresonator-based OFC (microcombs) can reach tens to hundreds of gigahertz (GHz), and various applications of microcombs, including telecommunications [15], metrology [16], and RF photonics [17], have been demonstrated. Intuitively, a dual comb can be directly obtained through combining

two microcombs that are generated in two separate microresonators with different free-spectral-ranges (FSRs) [8,9,11]. However, this scheme consumes double resources and goes against suppressing the common mode noise due to relative fluctuations between the two resonators. Recently, counter-rotating microcombs were realized in both a silica whispering-gallery mode (WGM) microresonator [18] and a silicon nitride microresonator [19]. The two counter-rotating combs are in the same polarization, and the repetition rates of the two generated combs are slightly different, which is caused by different pump-resonance detuning or pump power. Another scheme to generate a dual comb in a single microresonator is using the two orthogonal modes (i.e., transverse-electric [TE] and transverse-magnetic [TM] modes) of the microresonator. The asymmetric waveguide structure and imperfect fabrication process introduce different FSRs of the vertically polarized modes. When a couple of orthogonal continuous waves (CW) are coupled into the two vertical modes of a high- Q microresonator simultaneously, and their power reaches the threshold of the nonlinear parametric process, a vertically polarized dual comb will be generated in the microresonator [20]. Specifically, one comb with narrow bandwidth can be generated with rather low pump power with the assistance of the other polarized comb [21] due to the cross-phase modulation (XPM) effect between the two polarized modes.

In this paper, we experimentally demonstrate orthogonal polarized dual-comb generation in a high-index doped silica glass micro-ring resonator (MRR). The two vertically polarized pumps are self-oscillated in a gain fiber ring cavity in which an MRR is embedded. Compared with coupling external pump schemes, the self-oscillated pumps are self-stabilized via an intrinsic feedback mechanism, which effectively acts against thermal or mechanical fluctuations [22,23]. In our experiment, an over 300-nm-bandwidth dual comb is stably obtained, and the two combs could be simply separated through a polarization beam splitter (PBS). Our experiment realizes the proof-of-concept of orthogonal polarized dual-comb generation in one resonator, and this approach could be another feasible way of generating on-chip dual combs for microwave comb generation and dual-comb spectroscopy, etc.

2. DEVICE

The key device is an on-chip MRR, which is fabricated on high-index doped silica glass platform. The waveguide structure and fabrication process are the same as the device used in the dual-pump OFC generation experiments [22,24]. Figure 1(a) shows the schematic of the MRR with FSR of 49 GHz. Figure 1(b) shows the scanning electron microscope (SEM) image of the waveguide cross section with $2\ \mu\text{m} \times 3\ \mu\text{m}$ dimension. The calculated mode profiles for both the TE and TM modes are presented in Figs. 1(c) and 1(d), respectively. The calculated effective indexes for the TE and TM modes are 1.5613 and 1.56, and the relative FSRs of the two modes are 0.41361 nm and 0.41396 nm at 1558 nm, respectively, corresponding to about 44 MHz of FSR difference.

Both of the transmission and dispersion characteristics of the MRR are experimentally measured with the assistance of a fiber ring resonator (FRR) as shown in Fig. 2(a). The FRR

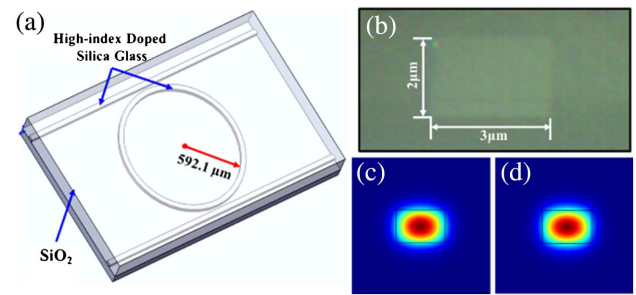


Fig. 1. Device schematic. (a) Schematic of the four-port high- Q MRR. The waveguide core is high-index doped silica glass, which is surrounded by SiO_2 cladding. (b) SEM image of the waveguide cross section with $2\ \mu\text{m} \times 3\ \mu\text{m}$ dimension. (c), (d) Calculated mode profiles for TE and TM modes, respectively.

consists of an optical coupler with splitting ratio of 99:1 and a segment fiber with length of ~ 6 m, corresponding to the FSR of 34.5 MHz at 1550 nm. The transmission traces of the MRR and FRR are measured using a tunable laser in the wavelength range from 1520 to 1600 nm. A dual-channel oscilloscope with two photodetectors is used to record the transmission traces. During the measurements, only a single polarization light transmits through the MRR each time by carefully tuning the polarization controller. And the polarization of the light transmitting through the FRR is fixed during the entire measurement. Figures 2(b) and 2(c) show the measured transmission traces for the TE mode and TM mode, respectively. The measured full width at half-maximum (FWHM) of the resonance of the MRR is 114 MHz for the TE mode and 94 MHz for the TM mode at 1560 nm, corresponding to the Q -factor of 1.69×10^6 and 2.05×10^6 , respectively.

Further, the dispersion characteristic of the MRR is obtained through analyzing the FSRs variation with wavelength, which is similar to the method of using an assistant fiber Mach-Zehnder interferometer (MZI) [25]. The FSR of the MRR at different wavelengths is obtained by counting the resonance number of the FRR between two neighboring MRR resonances with a computer program. And the effect of the FRR dispersion is calibrated by taking the fiber dispersion parameter into account. The resonance frequency ω_μ of the MRR can be approximately described with the dispersion parameters of the waveguide as [26]

$$\omega_\mu = \omega_0 + D_1\mu + \frac{1}{2}D_2\mu^2 + \frac{1}{6}D_3\mu^3 + \dots, \quad (1)$$

where ω_0 is one resonant angular frequency of the MRR, regarded as reference frequency. μ is the relative mode number of the resonance away from the reference frequency. $D_1/2\pi$ is the FSR of the resonator at the frequency ω_0 . D_2 is related with the second dispersion parameter β_2 in the context of the microresonator as $D_2 = -c/n_0D_1^2\beta_2$. D_3 is the third-order dispersion parameter. D_3 and higher-order terms are neglected. Thus, the parameter $\omega_\mu - \omega_0 - D_1\mu$ is directly related with the dispersion characteristic of the MRR. Figures 2(f) and 2(g) are the measured dispersion curve of the MRR for the TE mode and TM mode, respectively. The FSRs of the two vertical modes can be obtained by fitting the dispersion data using a

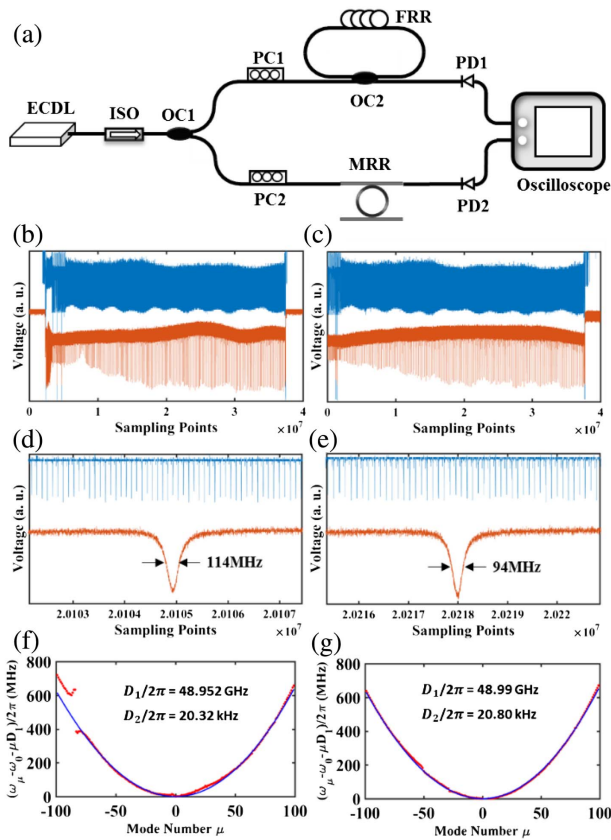


Fig. 2. Experimental measurement of the device characteristics. (a) Experimental setup for the measurement. The ECDL is a commercial tunable laser with linewidth of 100 kHz. The wavelength is swept from 1520 to 1600 nm in our measurements. The FRR comprises an optical coupler with splitting ratio of 99:1 and a segment fiber with length of ~ 6 m. During the measurements, the polarization of the FRR is fixed to one transmission mode, which is used as a ruler to measure the FSR of the MRR. By carefully tuning PC2, the transmission traces of the TE mode and TM mode are measured, respectively. (b), (c) The transmission traces of TE mode and TM mode together with the FRR transmission traces, respectively. (d), (e) The FWHMs of the two vertically polarized modes are 114 MHz and 94 MHz, corresponding to Q -factor of 1.69×10^6 and 2.05×10^6 , respectively. (f), (g) The measured dispersion curves of the two modes. The FSR of the TM mode is 38 MHz larger than that of the TE mode. ECDL, external cavity diode laser; ISO, isolator; OC, optical coupler; PC, polarization controller; PD, photodetector; MRR, micro-ring resonator; FRR, fiber ring resonator.

quadratic curve. The FSR difference of the two orthogonal modes is about 38 MHz, which is slightly different than the theoretical result and is probably introduced by the non-ideal fabrication process.

3. ORTHOGONAL POLARIZED DUAL-COMB GENERATION

Figure 3 shows the schematic of the orthogonal polarized dual-comb generation experiment. It contains two parts. The first part is a ring fiber laser, which is comprised of a high-output-power erbium-doped fiber amplifier (EDFA) as

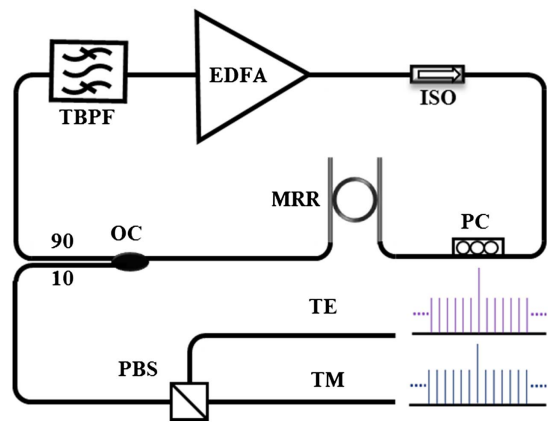


Fig. 3. Schematic of the orthogonal polarized dual-comb generation experiment. EDFA, erbium-doped fiber amplifier; ISO, isolator; PC, polarization controller; MRR, micro-ring resonator; TBPF, tunable bandpass filter; OC, optical coupler; PBS, polarization beam splitter; TE, transverse electric; TM, transverse magnetic.

gain medium, an isolator that forces unidirectional propagation in the laser loop, a polarization controller, a monolithic integrated high- Q MRR where dual orthogonal combs are generated by optical parametric oscillation effect, a tunable optical bandpass filter (TBPF) to select the pump wavelength together with the MRR, and an optical coupler to couple part of light out of the laser cavity. The total laser cavity length is about 40 m, corresponding to an FSR of 5.1 MHz. The second part is a polarization beam splitter to separate the orthogonal polarized dual-comb into two individual combs with orthogonal polarization.

In the experiment, the bandwidth of the TBPF is set to 0.4 nm with central wavelength of 1558 nm, which allows only one pair of TE and TM modes to lase simultaneously. Then increasing the driving current of the EDFA and tuning the central wavelength of the TBPF, two orthogonal wavelengths will lase when reaching the laser threshold. The output power of the two orthogonal polarization modes can be equalized by carefully tuning the PC and the central wavelength of the tunable filter. The two lasing wavelengths act as pumps for broadband dual-comb generation. Once the output power of the EDFA approaches 17.5 dBm (corresponding to the pump power inside the input bus waveguide ~ 14 dBm), new frequency lines will be generated. This threshold is almost one order less than the optical parametric oscillator (OPO) threshold of external pump (135 mW for the TE mode and 92 mW for the TM mode in theory). This is because the peak power is enhanced by supermode instability (SMI) as there are multiple fiber cavity modes oscillating simultaneously in a single resonance of the MRR. When the pump power increases to 30 dBm, an orthogonal polarized dual comb with over 300 nm bandwidth is obtained. The optical spectrum of the dual comb at the drop port of the MRR is shown in Fig. 4(a). Figures 4(b)–4(d) present the dual comb details with central wavelength located at 1530, 1558, and 1590 nm, respectively. The two orthogonal polarized combs get closer to each other along with the wavelength increasing due to the unequal repetition rate. The two combs can be easily separated through

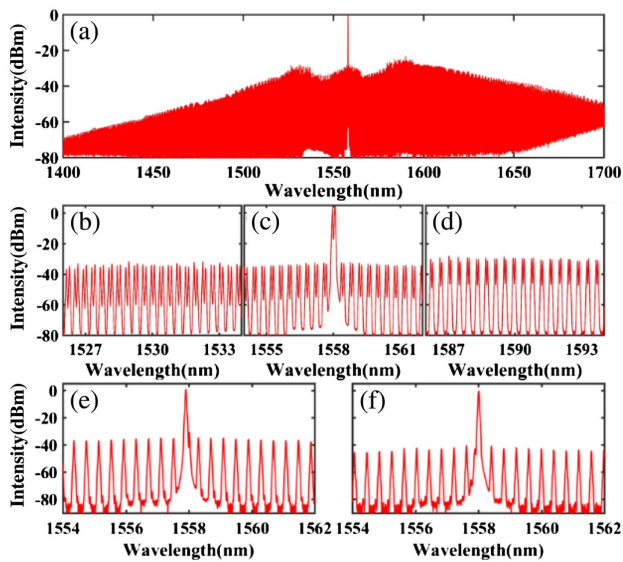


Fig. 4. Experimental results of the orthogonal polarized dual comb. (a) Optical spectrum of the orthogonal polarized dual comb with over 300 nm bandwidth. The two pumps are located at around 1558 nm. (b)–(d) Enlarged drawing of the orthogonal dual comb at around wavelengths 1530, 1558, and 1590 nm, respectively. (e), (f) The optical spectra of separated TM- and TE-polarized combs.

a PBS. Figures 4(e) and 4(f) present the optical spectra of the separated combs.

4. DISCUSSION

An orthogonal polarized dual comb is a proof-of-concept demonstration based on a self-locked scheme in a four-port high-index doped silica glass MRR. We observe self-termination free operation during our experiments attributing to the intrinsic feedback mechanism of the self-locked approach, which effectively acts against thermal or mechanical fluctuations of the ring parameters. As shown in Fig. 4, the bandwidth of the dual comb is over 300 nm, and the frequency spacing of the dual orthogonal combs becomes smaller along with the wavelength increasing due to the different FSRs of the two vertical modes. The two vertical polarized modes overlap with each other at around 1680 nm. When the two combs beat with each other after controlling the polarization, a microwave comb will be obtained. Figure 5 presents the overlapping beating RF spectra of pair frequency lines located at around 1558.8, 1567.7, 1576.7, 1585.7, and 1594.9 nm, respectively. Obviously, the beating RF spectra present high noise feature, which is caused by both of SMI and modulation instability (MI). The SMI is due to more than one main cavity mode lasing within one resonance of the MRR [27,28]. Intuitively, SMI can be solved by increasing the FSR of the main cavity and decreasing the bandwidth of the resonance of the MRR. Stable mode-locked lasers based on filter-driven four-wave mixing (FD-FWM) have been achieved by shortening the main laser cavity length [27,29]. However, the gain of the laser cavity will reduce along with the decreasing cavity length. If the laser power drops below the OPO threshold, the orthogonal polarized dual comb

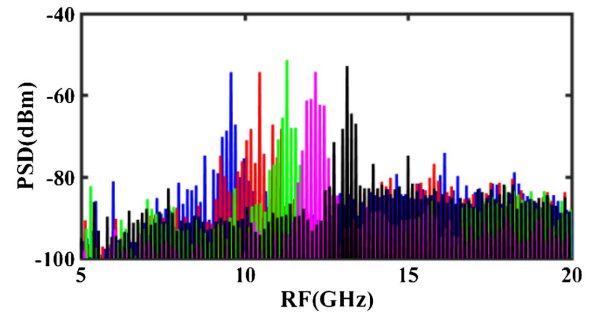


Fig. 5. Beating RF spectra of comb line pairs located at around 1558.8, 1567.7, 1576.7, 1585.7, and 1594.9 nm.

will not be generated. Another approach is using an MRR with higher Q -factor (such as $>10^8$), which has been successfully fabricated on several platforms [26,30–33]. A higher Q -factor corresponds to a narrower resonance linewidth, which will not only overcome the SMI but also reduce the needed pump power. For the current laser cavity, SMI will be overcome while the Q -factor of the MRR reaches 10^8 . Furthermore, in order to achieve a coherent microcomb, the detuning of the pump should be carefully controlled, such as soliton microcombs with far-red detuned pumps [26] and soliton crystals with slight detuning [34]. The intracavity power of the soliton crystals is similar to its precursor (MI combs), which proves the pump laser locates at around the peak of the resonance. So soliton crystals can be obtained independent of pump frequency sweeping speed, even with the thermal tuning method that has been realized on our platform. In the presented system, the frequency of the pump laser is easily locked to the resonance of the micro-resonator where the laser has the lowest cavity loss. Therefore, the presented system has the potential to realize soliton crystals, which would be a practical dual-comb source.

Further, an orthogonal polarized dual comb could also be generated through externally pumping the two modes simultaneously. The MRR used in our experiments owns a parabola dispersion curve for both the TE and TM modes at the communication band as shown in Figs. 2(f) and 2(g). So the MRR has the potential to generate soliton combs for both polarizations when the MRR is pumped by external lasers with applicable detuning and pump power. The orthogonal pumps could be generated with a single external-cavity diode laser in conjunction with an electro-optic modulator. The modulated frequency of the modulator should be carefully tuned to compensate for the resonant frequency spacing and detuning difference of the two modes. Thus, the dual-comb system will be simplified, and the coherent characteristic of the dual comb will be further enhanced. The dual comb could be split by an inline fiber PBS as shown in our experiments and used in the spectroscopy setup or precision distance measurement.

5. CONCLUSION

In summary, we demonstrate a proof-of-concept novel dual-comb source using the two orthogonal polarization modes based on a self-locked scheme in a single MRR. The experimental results show excellent stability attributing to the intrinsic feedback

mechanism. The dual comb could be simply split via an inline fiber PBS and PC. Besides, the dispersion characteristics of the MRR are also experimentally measured with an assistant FRR. Both of the two vertical modes of the MRR feature parabolic anomalous dispersion curves, which are suitable for OFC generation, even for soliton state comb generation. Our experiments provide a new approach to generate dual combs in a single microresonator and have the great potential in the fields of microwave generation and spectroscopy, etc.

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