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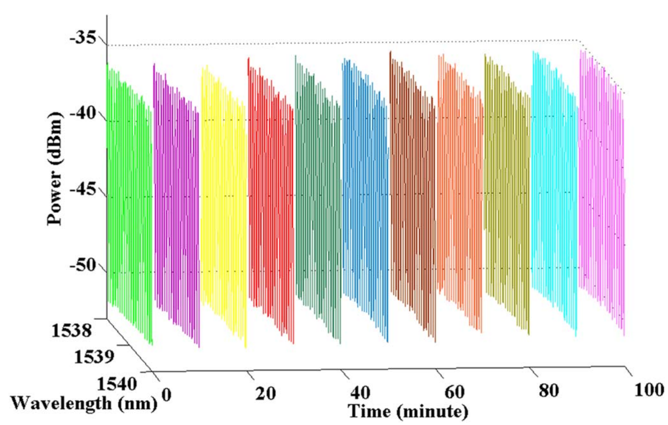

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Investigation of Multiwavelength Performance Utilizing an Advanced Mechanism of Bidirectional Lyot Filter

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Abstract: We investigate the performance of multiwavelength spectrum based on an advanced mechanism of a bidirectional Lyot filter. The generation and the variation of the multiwavelength spectrum are due to the effect of intensity dependent loss, which is induced from a semiconductor optical amplifier and its combination with a polarizer. By using the bidirectional configuration, a flat spectrum of 96 number of lines within 5 dB bandwidth is generated at current setting of 350 mA. The extinction ratio of the multiwavelength spectrum is high at 15 dB even though the line spacing is 0.1 nm. Multiwavelength flatness is better using the bidirectional Lyot filter configuration due to the effect of double interference. Additionally, different intensity and polarization angle are also found to be influencing the multiwavelength spectrum.

Index Terms: Multiwavelength fiber ring laser, bidirectional Lyot filter, semiconductor optical amplifier, intensity dependent loss.

1. Introduction

Multiwavelength fiber ring lasers (MFRLs) have attracted many researchers due to their prospective applications in optical communication, optical instrument testing and optical signal processing [1]. With rapid development of these laser applications, it is interesting to explore and investigate the MFRL. The MFRL based on erbium doped fiber amplifier (EDFA) has limited number of lines due to homogenous gain broadening of erbium ions, which leads to high mode competition. This problem can be solved by replacing the EDFA with an inhomogeneous broadening gain medium such as semiconductor optical amplifier (SOA) and Raman amplifier. Another alternative is by inserting a mode competition reducer like piezo-electric transducer or nonlinear device to the fiber laser system for a flat and stable MFRL. Nonlinear devices have been utilized in a laser cavity to induce an effect of either wavelength dependent loss [1], intensity dependent transmission (IDT) [2]–[6] or intensity dependent loss (IDL) [7]–[15]. These effects are induced by nonlinear polarization rotation (NPR) and work as an intensity equalizer to generate a flat MFRL to solve the issue of mode competition within the laser cavity.

Choosing the right comb filter is important in obtaining the best performance of MFRL. Many extensive researches have generated multiwavelength using different types of comb filters such as

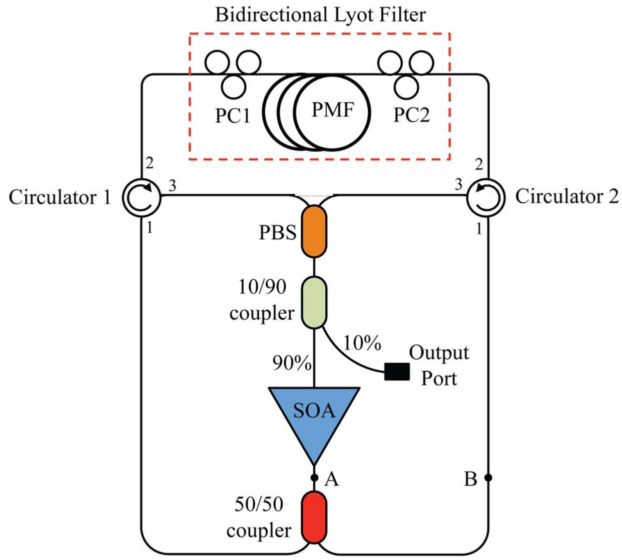

Fig. 1. Experimental configuration of the MFRL generation based on an advanced mechanism of bidirectional Lyot filter.

Mach–Zehnder interferometer [1], [16], Sagnac interferometer [2], [12], [14], [15] and Fabry–Perot interferometer [7], [10], [17]. One attractive option for comb filter is the Lyot filter, which has been demonstrated based on a segment [3]–[5], [8], [9], [13], [18] and two cascaded birefringent fibers [6], [19]. Multiwavelength spectrum generation via Lyot filter is attractive due to its simple configuration, low loss and good stability. In recent years, with the exception of Lyot-Sagnac filter, most of MFRL realizations based on Lyot filter were in unidirectional path [3]–[6], [8], [9], [13], [19]; with only one article in our knowledge reported MFRL in bidirectional path [18]. In their research, the wavelength tunability was achieved by non-simultaneous bidirectional light propagation. However, the MFRL based on simultaneous propagation in a bidirectional Lyot filter has never been reported.

In this paper, we realized a MFRL based on an advanced mechanism of bidirectional Lyot filter in which the counter propagating lights travel concurrently. The best performance of the laser has 96 number of lines within 5 dB bandwidth and high extinction ratio (ER) of 15 dB even with narrow line spacing. The double interference of light based on the bidirectional configuration produces a better multiwavelength flatness as compared to the unidirectional configuration. The IDL effect on multiwavelength spectra at different SOA current is studied as well. It is also found that without proper adjustment of polarization angle (PA), the multiwavelength performance is reduced.

2. Experimental Setup

The experimental setup of our proposed MFRL based on the bidirectional Lyot filter is shown in Fig. 1. In the proposed structure, SOA manufactured by QPhotonics, model QSOA-1550, was used as the gain medium. The SOA was driven by a laser diode controller from ILX Lightwave, model LDC-3900. The SOA has an operating maximum current and center wavelength of 400 mA and 1530 nm, respectively. In this paper, two polarization controllers (PCs) were used to control the relative phase difference between two orthogonal polarization state (PS) of light in a polarization maintaining fiber (PMF) [20], since the PS of light in a single mode fiber propagates arbitrarily. In the meantime, the half wave plate (HWP) of the PC works to adjust the PA, which is the angle of polarization direction of light to the birefringent axis of the PMF. The PCs combination with a PMF formed the bidirectional Lyot filter, which was used to slice the amplified spontaneous emission (ASE) of SOA into multiwavelength spectrum. Meanwhile, a polarization beam splitter (PBS) was employed as a polarizer and a light combiner. The PBS was also utilized to give an output of linearly polarized light without the use of PCs to control the PS before entering the PBS inputs. The

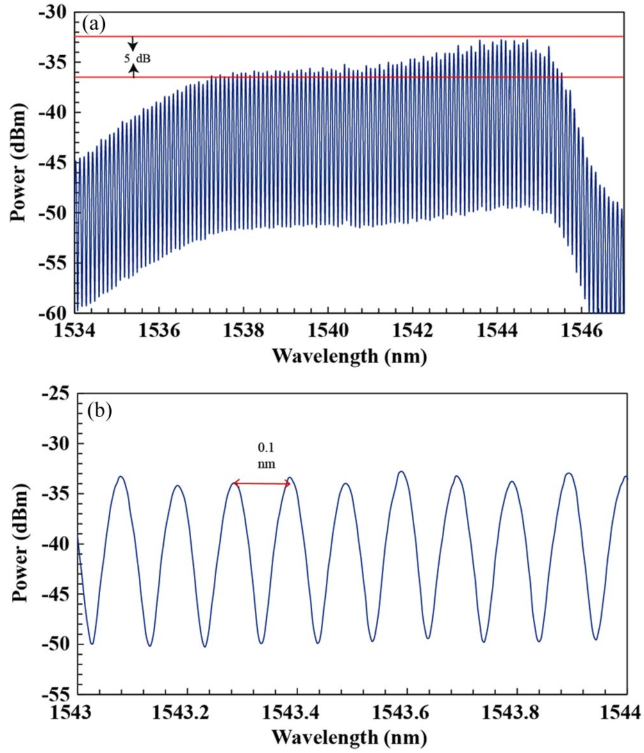

Fig. 2. The flat MFRL spectrum at 350 mA. (b) Magnified view of the spectrum from 1543 to 1544 nm.

combination of the polarizer with SOA induces IDL effect, which is important to equalize the lasing lines of multiwavelength spectrum. In the meantime, two circulators worked to ensure the light was routed in and out of the bidirectional Lyot filter in proper direction. These components were also employed to prevent the light from the SOA input from entering the bidirectional Lyot filter. The Panda-type PMF has birefringence (B) value and length of 4.5×10^{-4} and 53.2 m, respectively. A 50/50 output coupler was used to evenly distribute the light from SOA output to the Lyot filter. Finally, a 10/90 output coupler was used to extract the multiwavelength spectrum output to an optical spectrum analyzer (OSA). The OSA resolution and sensitivity settings were fixed at 0.02 nm and "high1", respectively throughout the experiment.

The operation principle of multiwavelength generation based on the bidirectional Lyot filter is as follows. First, the light from SOA output was split into halves via 50/50 coupler. Both lights were then directly routed through Circulator 1 and Circulator 2 in clockwise (CW) and counter-clockwise (CCW) directions, respectively in a counter-propagating manner. The polarization directions of the lights were set to 45° with respect to the birefringent axis of the PMF, as the PS of lights that passed through the PCs are in arbitrary propagation. At 45°, each light was refracted into two orthogonal lights propagating along the fast and slow axes of the PMF. The orthogonal lights traveled at different speed due to different refractive index of the PMF axes, but at the same amplitude and PS, before combining in-phase at the end of each path and accumulating phase differences. This is the process of constructive interference, which generates a sine-like transmission and defines our multiwavelength generation. In this laser operation, two constructive interference lights were present concurrently in CW and CCW directions. The interfered lights then combined and polarized in PBS, before going to the 10/90 output coupler. At the output coupler, 10% of the light went to OSA, while the other 90% was fed back into the ring cavity to continue the laser oscillation.

The IDL effect within the ring cavity is induced from NPR effect in SOA and its combination with polarizer. In our work, the IDL effect acted as an intensity equalizer to achieve a flat and stable multiwavelength spectrum. It is also beneficial to investigate the relationship between IDL effect and multiwavelength flatness at different intensity. In the working state of IDL, the transmission value is

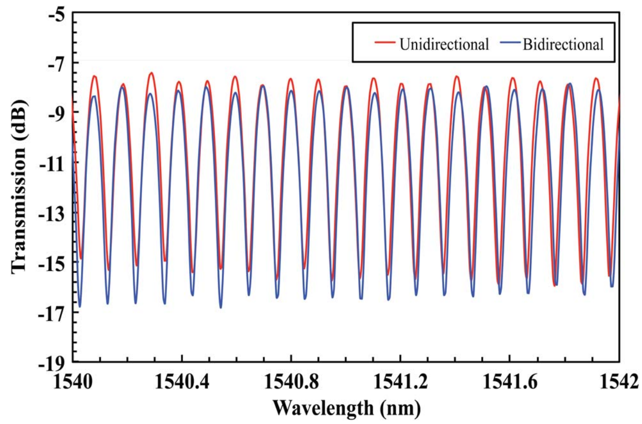

Fig. 3. The measured transmission spectra of unidirectional and bidirectional of Lyot filter.

inversely proportional to the input intensity [4]. Also, in this working state, the cavity loss increases with intensity due to larger PA between polarization direction of light and birefringence axis of the PMF [15]. Hence, it is important to have a high cavity loss in the cavity so that equalized lasing lines can be generated [7]. Meanwhile, the line spacing of the multiwavelength spectrum is determined using the equation $\Delta\lambda = \lambda^2/\mathrm{BL}$, where L and λ is the PMF length and the operating wavelength, respectively.

3. Results and Discussions

In this experiment, a high SOA drive current of 350 mA was used in accordance with our need for high intensity in the cavity. The output percentage of coupler and the L was maintained at 10% and 53.2 m, respectively for the entire experiment. Meanwhile, the PCs were adjusted until the best performance of multiwavelength spectrum was achieved. With these settings, a multiwavelength spectrum is obtained as depicted in Fig. 2(a). The spectrum has 96 number of lines within 5 dB bandwidth, and centered around 1543 nm. Fig. 2(b) is a magnified view of the spectrum in Fig. 2(a), which allows accurate measurement of the line spacing. From the figure, the measured line spacing is 0.1 nm and agrees well with the equation of line spacing. In this paper, the ER value is found to be at 15 dB even though the line spacing is 0.1 nm. The ER value is greatly enhanced due to the double interference of light accorded by the bidirectional Lyot filter. The use of longer PMF could increase the number of lines but results in lower ER value because the gain in the cavity, with the help of the intensity equalizer, is fairly distributed among the higher number of lines. Note that the 0.1 nm line spacing in our work is one of the narrowest ever reported for SOA-based MFRL. The best line spacing of 0.08 nm is reported in [2] but with a substantial trade-off of only 5 dB ER.

Using the same setting, the multiwavelength performance is investigated for different Lyot filter configurations. In this case, a unidirectional Lyot filter was realized by simply removing the 50/50 coupler and connecting the SOA output to the port 1 of Circulator 2 (point A to point B as illustrated in Fig. 1). Hence, the light from SOA output was routed only to Circulator 2 and made a unidirectional pass within the Lyot filter. In order to understand the behavior of these fiber laser architectures, the transmission spectrum of Lyot filters was characterized beforehand as depicted in Fig. 3. The experimental results show that both filters produce identical transmission response. The line spacing for both filters is around 0.1 nm that agrees well with the related equation mentioned previously in the Experimental Setup section.

The performance of multiwavelength laser using either a unidirectional or bidirectional Lyot filter was investigated using the same procedure that produced Fig. 2. The laser outputs from these fiber laser configurations are illustrated in Fig. 4. From the figure, the multiwavelength spectrum based on bidirectional setup has better flatness than the unidirectional configuration. As illustrated in Fig. 4(a), the spectrum flatness based on the unidirectional configuration exhibits significant peak power

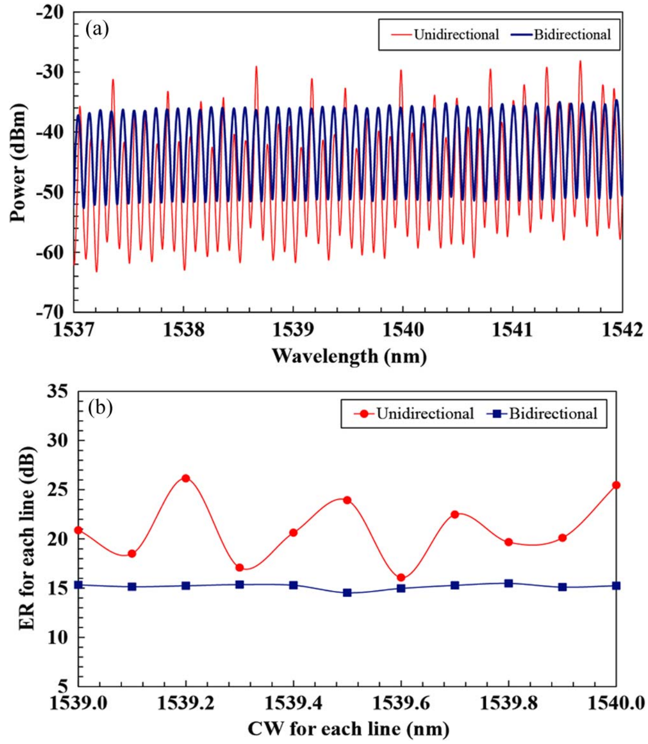

Fig. 4. (a) The MFRL spectrum comparison between unidirectional and bidirectional configuration. (b) ER against CW for each line at different configurations at 1 nm span.

variations across the observed wavelength range as compared to the bidirectional configuration, even with PCs adjustment to flatten the multiwavelength spectrum. From our observation, the bidirectional configuration has a flatter spectrum than the unidirectional configuration because of the effect of double interference of light that reshapes the interfered lights and flattens the multi-wavelength spectrum [15]. Hence, in this laser configuration, the use of bidirectional configuration plays a major role in obtaining a flatter spectrum. Fig. 4(b) demonstrates another performance parameter, ER value, which is plotted for each line within shorter wavelength span from 1539 to 1540 nm. From the figure, the maximum and the minimum ER discrepancies of unidirectional and bidirectional are 10.08 dB and 0.95 dB, respectively.

Next, we observed the intensity dependence to the multiwavelength performance. In this investigation, the SOA current was decreased while the other settings used to obtain the output in Fig. 2 were maintained. Note that, the two spectra as depicted in Fig. 5 are the flattest via PCs adjustment. As can be seen in the figure, the number of lines is lesser with lower SOA current. The number of lines within 5 dB bandwidth is decreased to 70 and 31 for SOA current of 250 mA and 150 mA, respectively. This is because, at lower current, the loss is greater than the gain at the extinct lasing lines. In other observation, the multiwavelength flatness is worse at lower SOA current. This phenomenon is due to the lower cavity loss within the ring cavity during the working state of IDL. The flatness deterioration proves that the working state is indeed IDL. If the flatness is reduced with higher intensity, then the working state is IDT, as demonstrated in [4]. Other realization of intensity dependent to different flatness was reported in [21] where the flatness of multi-wavelength spectrum is increased with intensity by adding another SOA. Meanwhile, the use of current below 150 mA further decreases the number of lines. It is also worth noting that the threshold current for lasing is around 100 mA. Therefore, the use of current below 100 mA is not considered in this study.

Again, by using the same setting as Fig. 2, both HWPs of PC1 and PC2 were varied to check its effect to the multiwavelength spectrum. As can be seen in Fig. 6, the performance of the

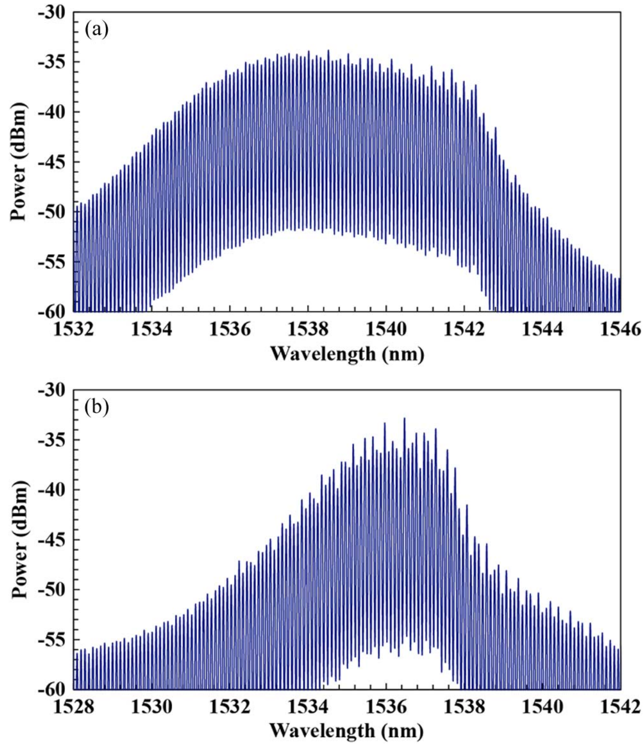

Fig. 5. The spectrum of MFRL when the current is reduced to (a) 250 mA and (b) 150 mA.

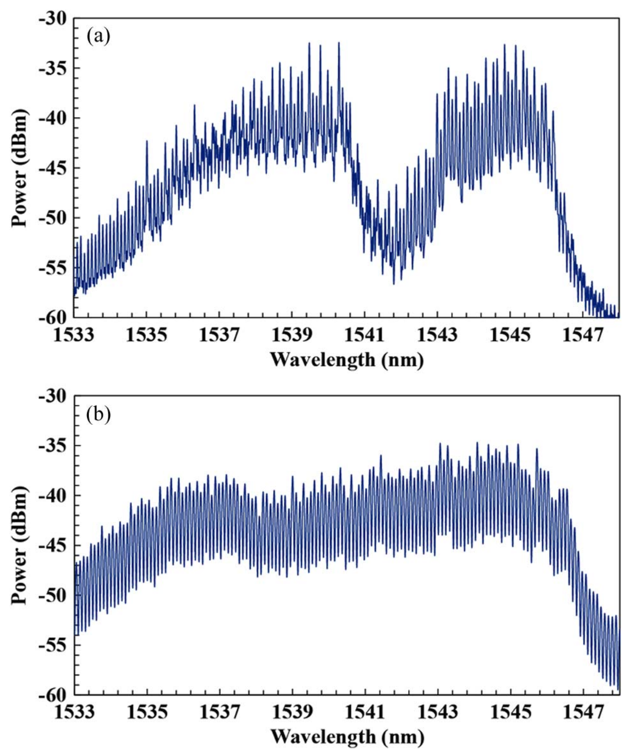

Fig. 6. Two different multiwavelength spectra under different PA.

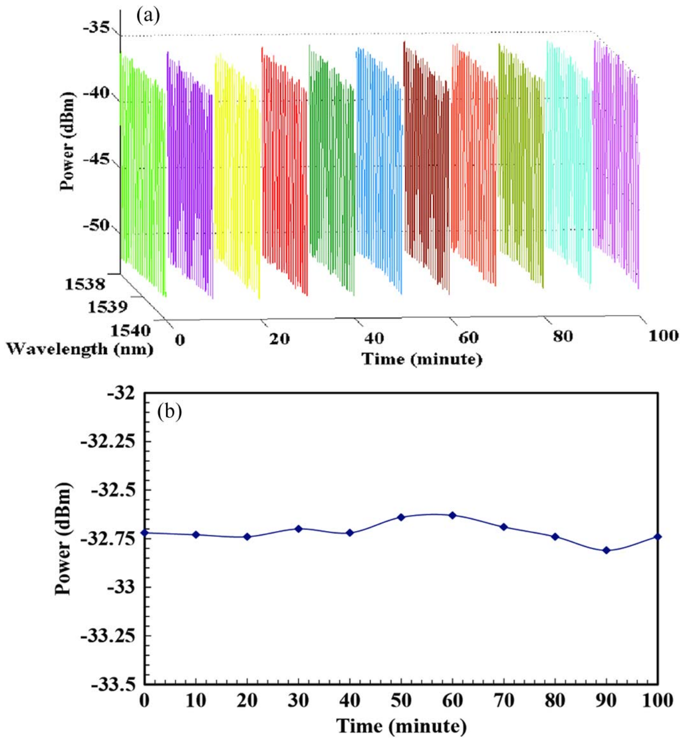

Fig. 7. (a) The MFRL stability under 100 minutes time frame and (b) the average peak power of spectrum line recorded every 10 minutes.

multiwavelength outputs deteriorates with random adjustment of the HWPs. The multiwavelength spectra are not evenly distributed over the wavelength range and ER value is lower as well. This is due to the different PA setting via HWPs adjustment. Thus, it is concluded that the best performance of multiwavelength spectrum based on the bidirectional Lyot filter is at PA of 45°, with the help of IDL effect as the intensity equalizer.

To check the MFRL stability, the spectral profile from 1538 to 1540 nm is recorded every 10 minutes at room temperature. As depicted in Fig. 7(a), each spectrum shows no sign of peak fluctuation and the lines are well maintained during the 100 minutes scanning period. The average peak power of the 20 spectral lines within this 2 nm span for the 10 minutes intervals is plotted in Fig. 7(b). From this figure, no significant laser fluctuation is observed in the 100 minutes time frame, with only a maximum of 0.2 dB power difference. This shows that the MRFL stability is good over long operational period and practical for the applications mentioned earlier in the introduction [1].

4. Conclusion

In conclusion, we have demonstrated, for the first time, a multiwavelength generation based on an advanced mechanism of Lyot filter. The Lyot filter has a bidirectional configuration in which the counter propagating lights travel concurrently. The multiwavelength performance is investigated at different configuration, intensity and PA. The flatness of multiwavelength spectrum using the bidirectional configuration outperformed the unidirectional configuration due to the double interference of light in the bidirectional Lyot filter. In the working state of IDL, high intensity in the cavity causes high cavity losses, and this is essential in producing the best flatness in multiwavelength generation. The best performance is at 350 mA of SOA current, which generates 96 number of lines within 5 dB bandwidth, with high ER and narrow line spacing of 15 dB and 0.1 nm, respectively. The IDL effect is also a factor in the variations of multiwavelength spectrum at different intensity. At different setting of PA, the lasing lines of the multiwavelength spectrum are uneven. The multiwavelength generation is stable with dithering below 0.2 dB.

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