Widely Tunable Near-Infrared Wavelength Conversion Based on Central and Off-Central Multiperiod Grating Pumped by a Compact Fiber Laser

WEN LIU, SHUANGGEN ZHANG, AND JINLEI LIU
Tianjin Key Laboratory of Film Electronic and Communication Device, Tianjin University of Technology, Tianjin 300384, China
Corresponding author: Shuanggen Zhang (shuanggenzhang@163.com)

ABSTRACT Tunable near-infrared sources are highly demanded due to their various applications in biomedicine, printing, barcode technology, and optical storage. In this paper, widely central phase-matching wavelength tunable and high efficiency are demonstrated in theoretically and experimentally, pumped by a compact all-polarization-maintaining (PM) 9-character cavity fiber laser operating near-infrared (785 nm) based on a multiperiod grating. The wavelength tuned at about 18.2 nm as the grating period changed 1 µm. A wide spectral tuning of 42 nm (from 776 nm to 818 nm) and high efficiency about 12.3% have been obtained. Besides, we discovered that the non-central second harmonic can also be generated from the second harmonic generation caused by strong phase mismatch, and the sum frequency generation (SFG) on account of the nonlinearity of the crystal. The result shows that the central and off-central phases match harmonics to form continuous broadband at some temperatures and grating periods, which can be widely exploited for wavelength conversion and tunable channel output.

INDEX TERMS Optical tuning, optical harmonic generation, nonlinear optics, periodic structures, gratings.

I. INTRODUCTION

The demand for tunable and broadband sources is increasing due to their various applications, especially in biomedicine and optical storage analysis [1]. One promising approach is the wavelength conversion of available lasers in nonlinear materials in the absence of suitable sources [2]–[5]. When the laser is transmitted in a nonlinear medium, a new wavelength is generated under phase-matching conditions, and quasi-phase-matching (QPM) is a common and effective method to achieve tunable wavelength.

Cavity design and optimization of continuous pump cavity have been widely used to control the cavity type, which also miniaturizes the laser. Increasing the efficiency of the resonant cavity structure has been investigated based on the nonlinear periodically poled lithium niobate (PPLN) crystal. The maximum output power was increased to 70 mW using the inner folding cavity structure in the mid-infrared idle wavelength of 3.66 µm [5]. Further, in 2018, a compact three-mirror linear cavity with plane and concave mirrors was experimentally and theoretically demonstrated, and its power density on the nonlinear crystal was improved by optimizing the concave radii of cavity mirrors [6].

Nevertheless, the steep adjusting accuracy of the resonant cavity is difficult to fulfill and thus limits its widespread use for wavelength tuning. The capability of quasi-phase-matched nonlinear optical frequency conversion combined with temperature control has been studied for realizing wavelength tunability based on a solid-state laser directly pumping a quasi-phase-matched optical parametric oscillator [7], [8]. The grating period of MgO: PPLN ranged from 29.52 to 31.59 µm, tuning the band from 3.0 to 3.8 µm [9]. However, the obtained wavelength tunable bands are mostly concentrated in the mid-infrared region, and studies on wavelength tuning in visible and near-infrared wavelengths are few. In 2018, an all-solid-state tunable CW orange laser based on single-pass sum frequency generation has been reported. The output wavelength could be tuned up to 5.66 nm by varying the operating temperature and the position of focusing inside the step-chirped crystal [10].
QPM is achieved when polarization directions are along the optical axis direction. The ginseng light has e-direction polarization, and their conversion coefficient is directly related. The pumped light monochromatic, the refractive index and temperature in the nonlinear matching factor close to 0, and $D$ where $D$ in Fig. 1, which shows that the largest matching wavelength of 1600 nm is selected for simulation as follows [14]–[16]:

\[
D(\Omega) = \gamma Ld_m \sin \left( \frac{(\Delta k_i - K_1 + \delta \nu \Omega) L}{2} \right) \quad (1)
\]

where $\gamma \equiv 2\pi/(\lambda_1 n_2)$, $\lambda_1$ is the fundamental harmonic wavelength, and $n_2$ is the refractive index of the SHG. $L$ is the crystal length, $d_m$ is the amplitude of the $n$th Fourier component of the grating, $\Delta k_i$ is the carrier k-vector mismatch at different periods or temperatures, $K_i = 2m\pi / \Lambda_i$, and $m$ is the QPM order. To obtain a high conversion efficiency, it is common to take $m = 1$, which indicates the polarization reversal cycle $\Lambda_i$ is the grating period. $\delta \nu = 1/\mu_1 - 1/\mu_2$ is the group velocity mismatch parameters. $\Omega = 4\pi c/\lambda_1 - 4\pi c/\lambda_0$ which is the angular frequency variation range of the second harmonic and $\lambda_0$ is the central wavelength of the fundamental harmonic.

The phase-matching factor can be represented as follows [17]–[19]:

\[
k(T, \lambda) = \frac{4\pi}{\lambda_1} \left[ n_2(T, \lambda_2) - n_1(T, \lambda_1) \right] - \frac{2\pi}{\Lambda_i} \quad (2)
\]

where $n_1$ is the refractive index of the fundamental harmonic, the refractive index and temperature in the nonlinear conversion coefficient are directly related, the pumped light and the ginseng light have e-direction polarization, and their polarization directions are along the optical axis direction. QPM is achieved when $k(T, \lambda) = 0$. Since the band of the input fundamental harmonic is determined, we can alter the period ($\Lambda$) or temperature ($T$) to achieve phase-matching.

To facilitate the follow-up research, a central phase-matching wavelength of 1600 nm is selected for simulation in Fig. 1, which shows that the largest $D$ is the phase-matching factor close to 0, and $D$ sharply decays when the phase-matching factor moves away from the central phase-matching wavelength, approaching 0. The intensity is nearly two orders of magnitude less than the central phase-matching when the mismatch wavelength was about 1570 nm. In our experiment, the time domain pulse of the femtosecond magnitude was adopted, strong noncentral phase-matching harmonics could still be observed.

The maximum intensity of second harmonic is at $\lambda_2$ as shown in Fig. 2(a), when the period of the grating central phase-matching of the central wavelength $\lambda_i$ of the fundamental wave, where $\lambda_1 = 2\pi c/\omega, \lambda_2 = 2\pi c/2\omega$. The maximum harmonic is at $\lambda_2^*$ which intensity is less than $\lambda_2$ in Fig. 2(a) when the wavelength matching the center phase of the grating is $\lambda_1^*$, where $\lambda_1^* = 2\pi c/\omega', \lambda_2^* = 2\pi c/2\omega'$. The fundamental wave at $\lambda_1$ can still generate the second harmonic wave at $\lambda_2$ with weak intensity through the grating, as can be seen from Fig. 1. In addition, the SFG effect due to the nonlinearity of the crystal was found by $2\omega = (\omega + \Delta\omega) + (\omega - \Delta\omega)$, and a weak SFG response generated at $\lambda_2$ of the two frequencies. As discussed above, the noncentral

**Figure 1.** Normalized transfer function reformed by the phase-matching factor ($k$) and fundamental wavelength.

**Figure 2.** (a) Generated second harmonic transformed by the quasi-phase-matched grating in different fundamental waves. (b) Generated harmonics transformed by SHG and SFG.
phase-matching harmonics at \( \lambda_2 \) was generated due to the combined action of SHG and SFG, as shown in Fig. 2(b).

III. TUNABLE SHG

In this section, we consider the second harmonic wavelength tuned by changing the period and temperature of the multi-period grating at the central QPM. Besides, the noncentral phase-matching harmonics are further analyzed.

A. EXPERIMENTAL SETUP

The experimental setup of the second-harmonic wavelength conversion of the MgO: PPLN crystal is shown in Fig. 3(a). The output laser of 9-cavity laser is amplified by EDFA and then passed through the AP to measure the input power. The PC is used to reduce the reflection and improve the quality of the light source. Then the laser beam is focused on the grating through the focusing lens M1, and the output beam is concentrated into the detector by the lens M2, so as to observe the output power and waveform. All PM 9-character cavity fiber laser output to 1570 nm as the center wavelength of the fundamental harmonic, which is a passive mode-locked laser shown in Fig. 3(b). The pulse is divided into two pulses with the same intensity and opposite transmission direction from D to the nonlinear amplifying ring mirror, that is the CW and CCW. The asymmetric amplification of the two pulses and the accumulation of different nonlinear phase shifts, due to the asymmetric structure of the nonlinear amplifying loop mirror. The two pulses are combined at the coupler and interfere after one loop of transmission. The effect of the equivalent saturable absorber of the nonlinear amplifying ring mirror is achieved by adjusting the nonreciprocal phase shifter in the cavity, so as to realize the self-starting of the mode locking [20]–[23].

![FIGURE 3. (a) Experimental setup to evaluate SHG in a multiperiod grating with an all PM 9-character cavity fiber laser as a pump. EDFA, erbium-doped fiber amplifier; AP, attenuation piece, PC, polarization controller, M1, M2, mirror. (b) Internal structure of the all-PM 9-character cavity fiber laser. CW is a clockwise direction pulse and CCW is a counter-clockwise direction pulse, OCM is the output coupling mirror. (c) Multiperiod grating structure.](image)

We used a multiperiod grating with a sample size of 5 (L) \( \times 9.2 \) (W) \( \times 0.5 \) (T) mm\(^3\), which is shown in Fig. 3(c). The multiperiod grating ranges from 19.5 to 21.3 \( \mu \)m. Each cycle height is 0.7 mm, and the interval between the cycles is 0.2 mm. The grating period is changed by moving the position of the multi period grating on the glass platform, and the temperature tuning of the grating is realized by the temperature controller.

B. TUNABLE AND OFF-CENTRAL PHASE-MATCHING HARMONICS WITH THE CHANGED PERIOD

In this section, we experimentally observed and theoretically simulated second-harmonic tunability and off-central phase-matching harmonics regularity, based on the chosen multi-period grating and temperature parameters.

We characterized the tunability by accommodating the grating period at 150°C, which experimental results are representative. The experimental and simulation results of the versus between the second harmonic wavelength and the grating period are shown in Fig. 4(a) and 4(b) respectively. The wavelength of the second harmonic shifted to a longer wavelength due to the increase in the grating period. The experimental data agreed well with the simulated data. at 150°C and grating period of 19.5–21.3 \( \mu \)m. The experimentally found second-harmonic wave band is wider than the theoretical one when the grating period is 20.1 or 20.3 \( \mu \)m due to the nonlinear action of the crystals.

![FIGURE 4. (a) Experimental and (b) theoretical distribution of the second harmonics under different periods at 150°C. (c) Central SHG wavelength changing with the grating period. (d) The first derivative changing with the grating period.](image)

We further considered the second-harmonic spectrum at 25°C, 50°C, and 100°C to accurately describe the influence of SHG tunable based on the multiperiod grating. The central second-harmonic wavelength as a function of the period is shown in Fig. 4(c), where E denotes experimental (results) and T, theoretical (results). The theoretical and experimental
results are mostly consistent. The larger the phase-matching period of the fundamental harmonic incident on the corresponding position on the crystal, the larger the central wavelength of the second harmonic shifts in the longer-wavelength direction. Moreover, the 19.5∼21.3 \( \mu \text{m} \) multiperiod grating led to a wavelength tuning of about 33 nm.

According to Section 2, the relationship between the period \( \Lambda \), temperature \( T \), and wavelength \( \lambda \) can be obtained, where \( \Lambda = \frac{2\pi}{\Delta k} = \frac{\lambda_1}{n_1(T)} - \frac{\lambda_2}{n_2(T)} \). The fundamental harmonic \( \lambda_1 \) can be regarded as a function of period \( \Lambda \) when \( T \) is constant. The first derivative of this function \( \frac{\partial \lambda_1}{\partial \Lambda} = 2(n_2 - n_1) \) is simulated in Fig. 4(d). Note that \( \frac{\partial \lambda_1}{\partial \Lambda} \) is always greater than zero in the wavelength range from 1550 nm to 1640 nm. This illustrates that the fundamental harmonic monotonically increases as the period increases. In this case, the wavelength of the phase-matched fundamental wave shifts in the direction of the longer-wavelength region with the increase in the grating period, and the corresponding second harmonic also shifts in the same direction (Fig. 4(a)) for the temperature range 25°C∼150°C.

Furthermore, the wavelength bandwidth is appeared near 785 nm from a period of 20.3 \( \mu \text{m} \), that is, the wavelength of the quasi-phase-matched second harmonic is greater than 800 nm, which is defined as off-central phase-matching harmonics. The reason for this phenomenon has been explained in Fig 1. Meanwhile, the relative intensity of the phase-matching second harmonic decreased, and the relative intensity of the noncentral second-harmonic phase-matching increased with the increase in the grating period. Nevertheless, the experimental data gave noise relative to the theoretical data. In order to research the harmonic under large phase mismatch, the phase matching at the center wavelength of the fundamental wave at 1570 nm was selected as the center phase matching \( \Delta k = 0 \). The harmonic wave with the period of 20.3∼21.3 \( \mu \text{m} \) at 150°C was simulated.

As can be seen from Fig. 5(a), the degree of phase mismatch increases gradually as the grating period increases, which means the central phase matching fundamental harmonic is farther than 1570 nm. Therefore, the intensity of central phase matching harmonics gradually decreases. Nevertheless, the wavelength of non-central phase-matched harmonics is always concentrated around 785 nm and does not change with the change of the period, as shown in Fig 5(b). The reason is the central wavelength of the fundamental wave always is 1570 nm, no matter whether the grating period is changed or not. The harmonics caused by the large phase mismatched SHG and SFG will always exist, and the harmonic intensity of SFG effect will also unchanged. So, the intensity of the non-central phase-matched harmonics will be relatively enhanced.

We systematically investigated the pattern of the fundamental harmonic before and after the amplifier in Fig. 6(a) and Fig. 6(b). The bandwidth broadened after the amplifier but also created significant noise. As can be seen from Fig. 6(b), the intensity of the fundamental harmonic sharply decays after 1600 nm and gradually approaches zero. As a consequence, the intensity of the second harmonic derived based on QPM also sharply decays and gradually approaches zero.

The distributions of the 1600 nm QPM grating period at different temperatures are shown in Fig. 7. The period of quasi-phase-matched grating decreases as the temperature increases, thus, observing the noncentral phase-matched wavelength with the temperature increase is easier. Taking 150°C as an example, the matching period at 1600 nm is 20.3 \( \mu \text{m} \), and the noncentral phase-matching harmonic also starts to appear at 20.3 \( \mu \text{m} \).
large phase-mismatched period. It is concluded that the intensity of the second harmonic is strong when the wavelength of the periodic phase-matching of the grating is strong, and the relative intensity of the non-centrally matched second harmonic is weak; therefore, it is difficult to be observed.

However, when the wavelength of the periodic QPM of the grating is greater than 1600 nm (i.e., the wavelength intensity is weak), under the combined action of SHG and SFG effect, the noncentral phase-matching harmonics are relatively enhanced due to the weak intensity of the second harmonic generated by QPM. Compared to that of the phase-matched harmonic, the harmonic intensity of the harmonic with a large phase mismatch differs by about 4 orders of magnitude.

C. TUNABLE AND NONCENTRAL PHASE-MATCHING HARMONIC VARIED WITH TEMPERATURE

In previous sections, we found that the tunability of the second harmonic and the intensity of the noncentral phase-matching harmonics are affected by not only the period of the multiperiod grating but also temperature. Hence, we further studied the spectra of harmonics changing with temperature at a specific period, as shown in Fig. 8.

![Figure 8](image)

**FIGURE 8.** (a) Theoretical and (b) experimental results showing changes in harmonics with temperature at a period of 20.9 \( \mu m \). (c) Central SHG wavelength changing with temperature, where T and E are theoretical and experimental data, respectively. (d) The first derivative changing with temperature.

The spectrum diagrams with a period of 20.9 \( \mu m \) at 25°C, 30°C, 50°C, 100°C, 120°C, and 150°C were measured for further analysis, which can reflect the intensity characteristics of each temperature better. The second harmonic from the central phase-matching moved toward the longer-wavelength region with the temperature increase (Fig. 8(a) and Fig. 8(b)). We extended this work to the entire period of the multiperiod grating from 19.5 to 21.3 \( \mu m \). The function of the temperature and the central wavelength of the second harmonic in different periods were further calculated. Compared to the experimental and theoretical data in Fig. 8(c), we obtained that the central wavelength of the central phase-matching second harmonics moved toward the longer-wavelength region as the temperature increased. In addition, a wavelength tuning of approximately 9 nm was achieved from 25°C to 150°C.

We treated the fundamental wavelength as a function of temperature when the grating period is fixed and simulated the first derivative (\( \frac{\partial \lambda_1}{\partial T} \)) of it, as shown in Fig. 8(d). The calculated \( \frac{\partial \lambda_1}{\partial T} \) is always greater than zero over the period range of the multiperiod grating used, that is, fundamental wavelength monotonically increases as a function of temperature for a given grating period. Therefore, when the temperature increases, the wavelength of the fundamental wave and the corresponding second harmonic generated move toward the longer-wavelength region.

Similarly, in this section, we determined the period and changed the temperature to understand the effect of phase mismatch on SHG. It can also be observed in Fig. 6 that when the period is determined, the higher the temperature is, the farther the fundamental wavelength of the central phase matching is from the central wavelength 1570 nm.

Therefore, the phase mismatch will gradually increase as shown in Fig. 9(a), and the intensity of the second harmonic at the central phase matching will gradually decrease. Since the fundamental wave remains unchanged, the noncentral phase matched harmonics will always be concentrated around 785 nm. The numerical simulation results are shown in Fig. 9(b), and the harmonic intensity generated by SFG will also unchanged. Therefore, the relative intensity of noncentral phase matched harmonics will be stronger, compared with the central phase matched harmonics.

![Figure 9](image)

**FIGURE 9.** (a) Phase mismatch varying with temperature, T. (b) Noncentral phase-matching harmonics varying with temperature, T.

D. CONTINUOUS SPECTRUM AND TUNING RATE

The noise is accordingly amplified owing to the fundamental wave amplified by the amplifier, explaining why the noncentral phase-matching harmonics in the experimental
spectrograms give noise. Remarkably, center and off-center phase-matching harmonics contribute to the continuous spectrum at certain temperatures and grating periods. The spectra at the period of 21.1 µm and the temperature of 30°C confirm this, which is shown in Fig. 10.

![Image](image_url)

**FIGURE 10.** The spectra at the period of 21.1 µm and the temperature of 30°C.

The wavelength tuning accuracy with the grating period and temperature demonstrated in Fig 11. We define the periodic wavelength tuning ratio as the wavelength tuning range for every 1 µm change of grating period, and the temperature wavelength tuning ratio as the wavelength tuning range for every 1°C change of temperature. The periodic wavelength tuning ratio is 18.15 (nm/µm) at 25°C, and it increases with the increase of temperature, as shown in Fig. 11(a). Compared with the grating period, the wavelength of the temperature-tuned wavelength is smaller, the temperature wavelength tuning ratio is about 0.0725 (nm/°C) at 21.3 µm, and it gets greater as the period increases, which is given in Fig. 11(b).

![Image](image_url)

**FIGURE 11.** (a) Periodic wavelength tuning ratio. (b) Temperature wavelength tuning ratio.

As previously discussed, wide spectral tuning of about 42 nm could be achieved by adjusting the grating period from 19.5 to 21.3 µm and the temperature from 25°C to 150°C. In addition, we can tune the temperature or period according to the above tuning rate to get the desired wavelength tuning range, offering great flexibility for wavelength selection and diversity.

E. EFFICIENCY OF THE CENTRAL SECOND HARMONIC

We also analyzed the conversion efficiency under different conditions to study the performance of the central second-harmonic spectrum tuning more accurately. The input fundamental harmonic of all data in Figures 4-11 is 56mW. The maximum conversion efficiency was about 11.5% when the temperature was 25°C and the grating period was 20.1 µm under an input power of 56 mW.

The efficiency of the second harmonic of the center matching tends to decrease with the increase in temperature, when the period is determined, as shown in Fig. 12(a). In our actual operation, the power is lost through the lens, and in the actual optical path, we use two focused lenses, each of which is about 4% efficient. Therefore, the final observed conversion efficiency is reduced by about 8% compared to the theoretical conversion efficiency.

![Image](image_url)

**FIGURE 12.** (a) Efficiency changes throughout the cycle at different temperatures when the input power (P1) is 56 mW. (b) Efficiency changes throughout the cycle at different input power at 25°C.

We compared and analyzed the efficiency when the input power was 43 and 56 mW, as shown in Fig. 12(b). These results show that the smaller the input power is, the greater the output power becomes. The maximum conversion efficiency is about 4% when the input power is 43 mW, and the loss of two lenses is very similar to the theoretical conversion efficiency of 12.3%.

IV. CONCLUSION

We obtained a widely tunable, compact, efficient, near-infrared optical laser operating at 785 nm based on a multi-period grating. We experimentally and theoretically showed that a wide spectral tuning of about 42 nm can be realized from 776 to 818 nm and the theoretical efficiency can up to 12.3%. The wavelength tuned at about 18.2 nm as the grating period changed 1 µm and 0.07 nm with a temperature adjustment of 1°C. The unit tunable harmonic wavelength gradually increased with increasing temperature or period. We confirmed that strong off-central harmonics can still be observed in the large phase mismatch when the time domain pulse of the femtosecond magnitude was adopted. The combined effects of SHG and SFG at 785 nm are detected where the central phase-matching harmonics are weak. Remarkably, at certain temperatures and grating periods, the central and off-central phases match harmonics to form continuous broadband, which can be widely exploited for wavelength conversion and tunable channel output.

REFERENCES

[1] C. Yang, A. Wax, M. S. Hahn, K. Badizadegan, R. R. Dasari, and M. S. Feld, “Phase-referenced interferometer with subwavelength and subhertz sensitivity applied to the study of cell membrane dynamics,” *Opt. Lett.*, vol. 26, no. 16, pp. 1271–1273, Aug. 2001, doi: 10.1364/OL.26.001271.
[2] R. W. Boyd, *Nonlinear Optics*. San Diego, CA, USA: AP, 1990, pp. 15–19.

[3] B.-Q. Chen, C. Zhang, C.-Y. Hu, R.-J. Liu, and Z.-Y. Li, “High-efficiency broadband high-harmonic generation from a single quasi-phase-matching nonlinear crystal,” *Phys. Rev. Lett.*, vol. 115, no. 8, Aug. 2015, Art. no. 083902, doi: 10.1103/physrevlett.115.083902.

[4] S. K. Fedorova, G. S. Sokolovskii, M. Khomylev, D. A. Livshits, and E. U. Rafailov, “Efficient yellow-green light generation at 561 nm by frequency-doubling of a QD-FBG laser diode in a PPLN waveguide,” *Opt. Lett.*, vol. 39, no. 23, pp. 6672–6674, Dec. 2014, doi: 10.1364/OL.39.006672.

[5] D. G. K. Choge, J. Cryst. Growth, vol. 312, no. 8, pp. 1109–1113, Apr. 2010, doi: 10.1016/j.jcrysgro.2010.08.056.

[6] N. Umemura and D. Matsuda, “Thermo-optic dispersion formula for chiometric LiNbO$_3$”, *Opt. Lett.*, vol. 38, no. 6, pp. 860–862, Mar. 2013, doi: 10.1364/OL.38.000860.

[7] Y. Zhang, Y. Duan, Z. Wang, D. Zhang, J. Zhang, Y. Zhang, and H. Zhu, “Continuous-wave widely tunable MgO: PPLN optical parametric oscillator with compact linear cavity,” *IEEE Photon. Technol. Lett.*, vol. 30, no. 20, pp. 1756–1759, Oct. 15, 2018, doi: 10.1109/LPT.2018.2868736.

[8] Y. J. Ju, Y. Y. Chen, C. Wang, C. T. Wu, and G. Y. Jin, “Experimental study of multiple optical parametric oscillator based on MgO: APLN and its evolution analysis of back conversion,” *Acta Phys. Sinica*, vol. 64, no. 4, pp. 4420–4423, Feb. 2015, doi: 10.7498/aps.64.044203.

[9] W. Wang, T. Chen, P. Jiang, B. Wu, and Y. Shen, “High-power multichannel PPMgLN-based optical parametric oscillator pumped by a master oscillation power amplification-structured Q-switched fiber laser,” *Appl. Opt.*, vol. 51, no. 28, pp. 6881–6885, Aug. 10, 2012, doi: 10.1364/AO.51.006881.

[10] T. Jiang, Y. Cui, P. Lu, C. Li, A. Wang, and Z. Zhang, “All PM fiber laser mode locked with a compact phase biased amplifier loop mirror,” *IEEE Photon. Technol. Lett.*, vol. 28, no. 16, pp. 1786–1789, Aug. 15, 2016, doi: 10.1109/LPT.2016.2572167.

[11] R. Li, H. Shi, H. Tian, Y. Li, B. Liu, Y. Song, and M. Hu, “All-polarization-maintaining dual-wavelength mode-locked fiber laser based on Sagnac loop filter,” *Opt. Exp.*, vol. 26, no. 22, pp. 28302–28311, Oct. 2018, doi: 10.1364/OE.26.028302.

[12] N. Kuse, J. Jiang, C. C. Lee, T. R. Schibli, and M. E. Fermann, “All polarization-maintaining Er fiber-based optical frequency combs with nonlinear amplifying loop mirror,” *Opt. Exp.*, vol. 24, no. 3, pp. 3095–3102, Feb. 2016, doi: 10.1364/OE.24.003095.