Raman fiber laser harmonically mode-locked by exploiting the intermodal beating of CW multimode pump source

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Abstract: We report here the first demonstration of a harmonic mode-locked Raman fiber laser using the intermodal beating of a continuous-wave (CW) multiple-longitudinal-mode pump laser. By matching the Raman-cavity round-trip frequency with the intermodal-beating one of a 1064 nm CW pump source, harmonic mode-locking in phosphosilicate Raman fiber laser is stably initiated at the first-order Stokes of 1239.5 nm, and generates rectangular-shape nanosecond pulses with the pulse energy up to 4.25 nJ. Using the new type of mode-locking, the harmonic order can be discretely tuned from 78^{th}- to 693^{rd}-order, and the cavity supermode is suppressed up to 51.1 dB with the signal-to-noise ratio of more than 65 dB.

OCIS codes: (140.4050) Mode-locked lasers; (140.3550) Lasers, Raman.

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1. Introduction

Mode-locked fiber lasers (MFLs) have attracted intense research interests due to their widespread applications in fields such as spectroscopy, sensing, telecommunication, and biomedical research. At present, MFLs using various rare-earth-doped fibers can indeed achieve high-performance mode-locked pulses with the ultrashort pulse width, high peak power and good stability [1–6]. However, their spectral operation of such MFLs is limited to the particular gain bandwidth of the rare-earth dopants. Raman gain in optical fiber is available to overcome the spectral limitation, since the simulated Raman scattering can be excited virtually at any wavelength by providing a suitable pump source. Therefore, the use of Raman gain has great potential to access new wavelengths for mode-locking [7,8].

Using different active/passive mode-locking techniques [7–15], mode-locked Raman fiber lasers (MRFLs) have been investigated in recent years. In 2005, *Chestnut et al.* demonstrated a wavelength-versatile subpicosecond MRFL with the nonlinear amplifying loop mirror (NALM) [7]. Using the dissipative four-wave-mixing mode-locking technique [9], *Schröder et al.* obtained the MRFL with an ultrahigh repetition rate of 100 GHz. By incorporating a semiconductor saturable absorber mirror (SESAM) [10], MRFL at 1.6 μm was also presented. *Randoux et al.* have further proposed the mode-locked cascaded-Raman fiber laser by employing the nonlinear polarization evolution (NPE) [11]. Most recently, Raman fiber lasers mode-locked using carbon nanotubes [12] or graphene [13] have been successfully achieved by *Castellani et al.*

In this paper, we develop a new type of MRFL by well matching the intermodal-beating frequency of continuous-wave (CW) multiple-longitudinal-mode pump source with the cavity round-trip frequency (CRF). We refer to this technique as intermodal-beating mode-locking (IBML). Compared with those mode-locking techniques used in the previous MRFLs [7–13], the proposed IBML is capable of fully exploiting the Raman-gain advantages and releasing the limitation of pulse repetition rate, benefiting from its unique characteristics as follows: 1) using the intermodal beating of CW pump laser without requiring any specific mode-locking element (e.g. NALM, NPE, saturable absorber, active modulator); 2) allowing the convenient selection of mode-locking harmonic to obtain high repetition rate. Based on the IBML technique, we experimentally achieve a harmonic MRFL at the 1^{st}-order Raman Stokes of 1239.5 nm.

2. Principle of intermodal-beating mode-locking

Figure 1 schematically depicts the principle of the IBML technique in CW multimode-pumped Raman lasers. The IBML technique is under CW pumping and no specific mode-locking element in laser cavity. It seems counterintuitive that a CW intracavity Raman laser could be mode locked. In 1969, *Kuznetsova* analyzed theoretically that [16], using a CW multimode laser as Raman pump, optical pulses in Raman amplifier could be formed. Here, we further develop it

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into Raman lasers for realizing the IBML. In practice, the intermodal beating in a CW multimode laser always exists, and can lead to the quasiperiodic and weak fluctuations of optical amplitude at the beat frequencies (f_i), as usually observed from their radio-frequency (RF) spectrum. The amplitude fluctuations are weak and random so that the measured power still appears CW, and therefore it is usually thought to be neglectable and even detrimental in some practical applications. On the contrary, when a CW multimode laser is used to pump a Raman gain medium, the weak amplitude fluctuations can become very helpful for the proposed IBML. During the Raman-conversion process, the intermodal-beating amplitude fluctuation $I_p(f_i,t)$ of multimode pump laser is transferred to the Raman Stokes wave $I_s(f_i,t)$, which is determined by:

$$I_s(f_i,t) \propto exp[gI_p(f_i,t)l]. \tag{1}$$

Here g and l are the Raman coefficient and the length of Raman gain medium, respectively.

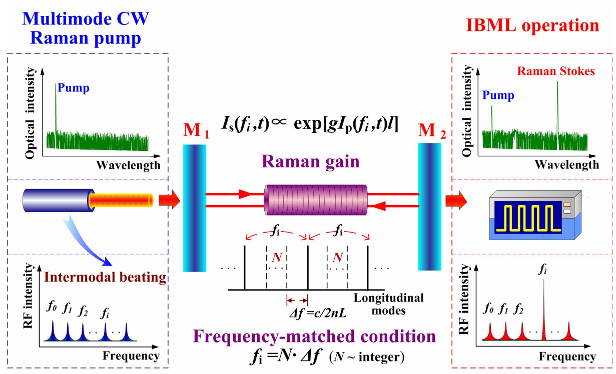

Fig. 1. Schematic principle of the IBML mechanism. ***n***: effective refraction index, ***L***: cavity length and ***c***: light velocity, $\mathbf{M}_1$, $\mathbf{M}_2$: reflective cavity mirrors.

Especially, if one further designs a Raman laser cavity with proper parameters so that the longitudinal-mode frequency spacing (Δf, i.e. CRF) well matches the transferred amplitude-fluctuation frequencies (f_i) of Stokes wave, a fixed phase relation will be built up among these longitudinal cavity modes with the frequency spacing of f_i. The phase-locking mechanism is similar to the active mode-locking based on an optical modulator, and the intermodal-beating of multimode pump laser is equivalent to the active optical modulator, because it induces the periodic amplitude modulation of Raman Stokes with the intermodal-beating frequencies (f_i). In other words, the stable IBML will be generated when the following frequency-matched condition is satisfied,

$$f_i = N \cdot \triangle f. \tag{2}$$

where N is the harmonic order. Based on such principle of mode locking, we can find the fundamental characteristics of the IBML. Firstly, the proposed IBML mechanism no longer requires any active/passive optical modulator or synchronous pulsed pumping, and it only needs the intermodal beating of CW multimode pump source. Moreover, a very high repetition rate by the IBML could be obtained, since the pump laser with ultrahigh intermodal-beating frequency can be found easily and the frequency-matched condition with a high harmonic order can be satisfied by selecting the value of Δf.

3. Experimental setup and characteristics of CW Raman pump

Based on the IBML principle, we performed the experimental studies as follows. The experimental setup of the proposed IBML-based Raman fiber laser is shown in Fig. 2. A 1064 nm

CW ytterbium-doped double-clad fiber laser (YDFL) is used to pump a spool of ∼650 m phosphorus-doped (P-doped) silica fiber through a 1064/1240 nm wavelength division multiplexer (WDM1). The P-doped silica fiber as Raman gain medium was manufactured by the Fiber Optics Research Center of Russian Academy of Science, and has the cut-off wavelength of 1000 nm, the zero-dispersion wavelength of about 1270 nm and the loss coefficients of 1.84 dB/km at 1064 nm. The Raman spectrum of the fiber has two Raman peaks [17] at the wavenumbers of ∼495 cm^{-1} and 1330 cm^{-1} which are assigned to the frequency shifts of SiO_2/GeO_2 and P_2O_5, respectively. The Raman coefficients (at 1064 nm) of the two peaks are about 0.8×10^{-3} and 1.3×10^{-3} $W^{-1}\cdot m^{-1}$. Owing to the higher gain coefficient of P_2O_5, we selected the Raman conversion of P_2O_5 for providing the laser gain in our experiment. The linear cavity for the first-order Stokes of 1240 nm is formed by two fiber loop mirrors (FLMs). A 1240/1310 nm WDM2 is used to prevent the occurrence of parasitical oscillation by the Raman conversion of SiO_2/GeO_2 from 1240 to ∼1310 nm. A length-variable fiber as cavity-mode matching element (Corning HI-1060 fiber) is used to control the CRF for satisfying the frequency-matched condition (i.e. Eq.(2)) of IBML. A 10:90 optical coupler (OC1) couples out 10% of oscillating light as laser output. The total cavity length is about 660 m with a fundamental CRF of ∼157 kHz, and the net-cavity dispersion is positive at the Stokes wavelength of 1240 nm. The output optical spectrum of this laser was monitored by an optical spectrum analyzer (OSA). The output pulsed characteristics were detected by a 10 GHz photodetector (PD) together with a 1 GHz digital storage oscilloscope (DSO), and were also analyzed by a RF spectral analyzer (RSA).

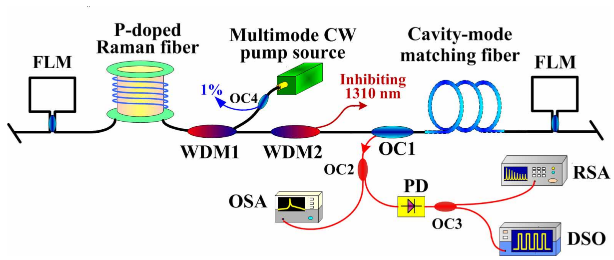

Fig. 2. Experimental setup of the harmonic MRFL based on the IBML technique. The OC2 and OC3 are 10:90 and 50:50 optical couplers at 1240 nm, respectively.

Since the Raman pump source is of the utmost importance for realizing the IBML operation, the 1% output power of our Raman pump source (i.e. the CW YDFL) was extracted by a 1:99 optical coupler (OC4) for studying its characteristics. As given in Fig. 3(a), the 3-dB linewidth around 1064.4 nm is 0.31 nm. Using a laser beam analyzer, the optical intensity distributions in both Figs. 3(b) and 3(c) show a good Gaussian shape which manifests the single-transverse-mode output of the YDFL. As a result, the intermodal beating of the YDFL could mainly occur among multiple longitudinal modes, and has been characterized as follows. As shown in Fig. 3(d), the intermodal-beating amplitude fluctuation from the oscilloscope trace of the YDFL output was not obviously observed due to the superposition of all the intermodal beats. However, one can see from Fig. 3(e) that the intermodal-beating frequency peaks in its RF spectrum regularly appear with a spacing of 2.43 MHz. It is especially noted that the RF intensity at 12.16, 24.32 MHz and their harmonic peaks is slightly stronger. One could be of more interest to these stronger RF peaks, because they are more favorable for realizing the IBML. As given in the insets of Fig. 3(e), the closed looks at the two peaks show their 3-dB beating-bandwidths of ∼100 kHz with the central frequencies of 12.157 and 24.315 MHz, respectively.

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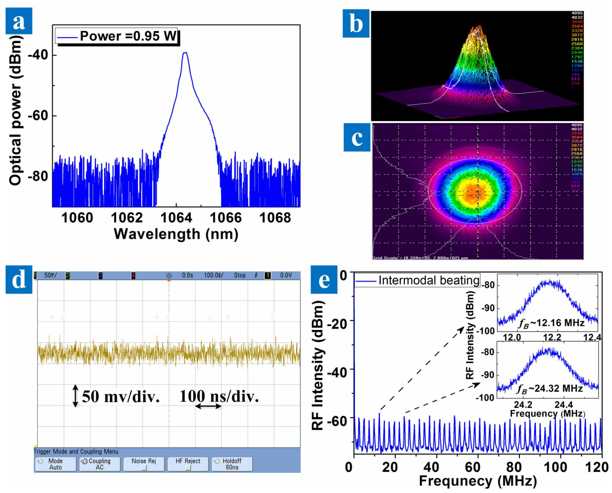

Fig. 3. **(a)** Optical spectrum measured at the YDFL power of 0.95 W. **(b)** and **(c)** are the 3-D and 2-D images for optical field distribution of the YDFL. **(d)** The oscilloscope trace of the YDFL output. **(e)** The measured intermodal-beating characteristics of the CW YDFL. Insets: the close look of the stronger beat peaks at 12.16 MHz (top) and 24.32 MHz (bottom).

4. Experimental results and discussion

In our experiment, when we purposely mistuned at first the frequency-matched condition of IBML by inserting an inappropriate length of cavity-mode matching fiber (CMMF), no self-started mode-locking could occur. Comparatively, by designing a 5.8m-long CMMF, the fundamental CRF is measured to be 155.60 kHz, 78-times of which exactly locates within the RF bandwidth of the 12.16-MHz beating-peak, namely, to meet the frequency-matched condition of the IBML. It was found that the self-started mode-locking easily occurred even at the

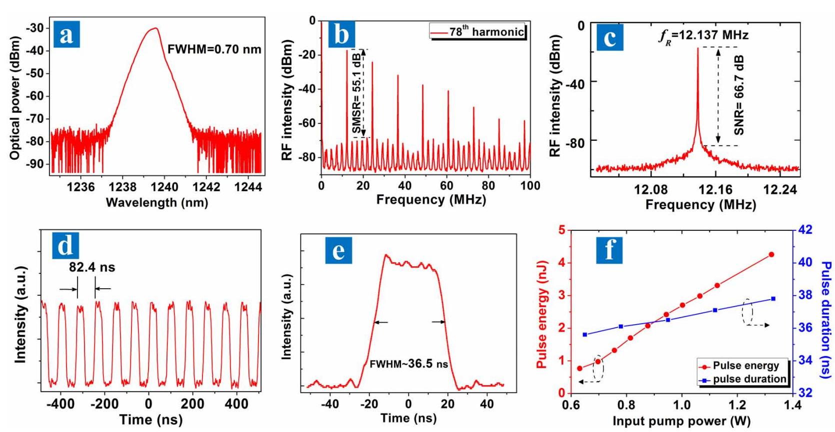

Fig. 4. **Characteristics of the 78^{th}-order harmonic IBML-based Raman fiber laser. (a)** The output optical spectrum at the first-order Stokes of 1239.5 nm. **(b)** Typical RF spectrum, and **(c)** The close look at the mode-locked frequency of 12.137 MHz. **(d)** Typical rectangular-shape pulse trains. **(e)** The single pulse envelope. **(f)** Pulse energy and pulse duration as a function of the input pump power.

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threshold pump power of 0.63 W. Figure 4 summarizes the typical characteristics of the IBML Raman fiber laser at the incident pump power of 0.95 W. As shown in Fig. 4(a), the mode-locked optical spectrum has a central wavelength at the 1^{st}-order Raman Stokes of 1239.5 nm and a full width at half maximum (FWHM) of 0.70 nm. Moreover, during our 2-hour test, the mode-locked optical spectrum under room-temperature operation remained almost unchanged, indicating the good long-term stability of the mode-locking. We also measured the RF spectrum of the mode-locked pulses. One can find from the Fig. 4(b) that the pulse repetition rate (f_R) is 12.137 MHz which coincides with the 78^{th}-order harmonic of the CRF, verifying the real occurrence of the IBML. The supermode suppression ratio (SMSR) of the harmonic mode-locking is as high as 51.1 dB, comparable to the highest SMSR of the reported harmonic mode-locking [18]. With a RF resolution bandwidth of 10 Hz, Fig. 4(c) gives the close look at 12.137 MHz. The RF signal-to-noise ratio (SNR) is more than 66 dB, indicating the excellent stability of the mode-locked pulses. The measured oscilloscope trace of the harmonic mode-locked pulse train is shown in Fig. 4(d). It is interesting that the IBML generated the rectangular-shape optical pulses with a period of 82.4 ns and a duty cycle of 45.4%. The single pulse envelope depicted in Fig. 4(e) has a pulse width of 36.5 ns, the rising/trailing edges of 13.9/11.6 ns and no noise-like structure. In addition, as shown in Fig. 4(f), we also measured the pulse width and the single pulse energy while increasing the pump power from 0.65 to 1.35 W. The pulse width has a slight broadening from 35.6 to 37.8 ns, and the single pulse energy increased linearly with the pump power. At the incident pump power of 1.35 W, the average output power and the pulse energy are 51.6 mW and 4.25 nJ, respectively, corresponding to the intracavity average power of 516 mW and the intracavity pulse energy as high as 42.5 nJ. With such large energy and high power of the intracavity pulses, the self-phase modulation (SPM) can be very strong in the nonlinear Raman cavity. It is known in theory [19] and experiments [20] that the SPM can dramatically enhance the broadening rate of the pulses in the normal dispersion regime and make soliton- or Gaussian-shape pulses to be rectangular-shape ones. Therefore, the formation of the rectangular-shape pulses in the IBML-based Raman laser is mainly attributed to the strong optical nonlinearity (e.g. SPM).

In order to clearly demonstrate the natural advantage of IBML for flexibly selecting the harmonic order of mode-locking, we also performed the IBML operation at the 155^{th}-order harmonic of the fundamental CRF. By changing the length of the CMMF to 0.7 m, the CRF became 156.79 kHz, 155-times of which exactly locates within the RF bandwidth of the 24.32-MHz beating-peak of the Raman pump. Namely, the frequency-matched condition of the IBML at the 24.32 MHz is well satisfied, but not satisfied at other intermodal-beating frequencies. Figures 5(a) and 5(b) show the typical RF spectrum of the harmonic mode-locking and the enlarged details at the fundamental RF peak, respectively. The fundamental RF peak locates at 24.302 MHz, confirming the realization of the 155^{th}-order harmonic mode-locking. The SMSR and the RF SNR of the 155^{th} harmonic mode-locking are 48.6 dB and 65.1 dB, indicates that the harmonic mode-locking is also stable. As given in the Fig. 5(c), the harmonic mode-locked pulses still have the rectangular-shape profile with a pulse period of 41.2 ns, a duty cycle of 39.6% and a pulse width of 15.2 ns. Moreover, the measured optical spectrum of the harmonic mode-locking is as the same as the 78^{th}-order harmonic one shown in the Fig.4(a). In addition, by precisely controlling the CRF with different lengths of the CMMF, in our experiment we also obtained the higher-order harmonic mode-locking, including the 311^{th}-order and 693^{rd}-order (corresponding to the f_R of 109.426 MHz) harmonics, etc.

5. Conclusion

In summary, we have proposed and demonstrated a harmonic MRFL based on the IBML mechanism to generate the rectangular-shape optical pulses in normal dispersion regime. The output

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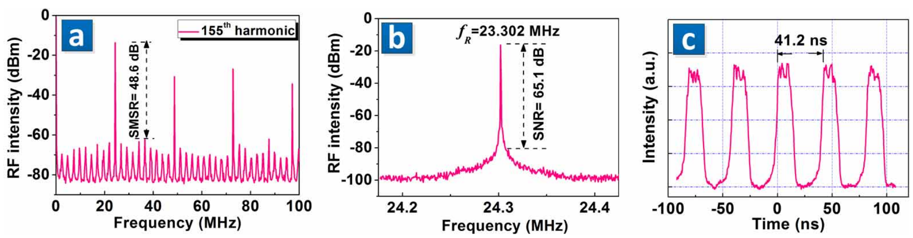

Fig. 5. **(a)** The RF spectrum of the 155^{th}-order harmonic mode-locking, **(b)** the close look at the mode-locked frequency of 24.302 MHz. **(c)** The typical oscilloscope pulse train of the 155^{th}-order harmonic mode-locking.

mode-locked pulses were obtained with 4.25 nJ pulse energy, >65 dB SNR and the selectable harmonic from 78^{th} to 693^{rd}-order. The proposed IBML technique shows the following advantages: 1) only using a CW multiple-longitudinal-mode pump source with the proper length of Raman cavity, without requiring any specific mode-locking element; 2) by controlling the CRF, the harmonic order of mode-locking can be conveniently selected. This method of mode-locking may be a new route for generating high repetition rate, large energy and arbitrary-wavelength pulses. Future research could be carried out as follows: 1) to study the IBML operation in the anomalous dispersion regime, 2) to explore the potential of the IBML technique for generating ultrahigh-repetition-rate optical pulses, and 3) to improve the pulse performances and the laser efficiency by optimizing the cavity designs.

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