2 μm Repetition-Rate Tunable (1-6 GHz) Picosecond Source

Jiarong Qin, Yafei Meng, Wenbin Gao, Yao Li, Labao Zhang, Jinlong Xu, Shining Zhu, and Fengqiu Wang

Abstract—**We have for the first time experimentally demonstrated a high repetition-rate picosecond fiber laser source at 2 μm by spectrally masked phase modulation technique, where a phase modulator driven by a sinusoidal RF signal and a fiber Bragg grating are used to convert the output of a 2 μm continuous-wave single-longitudinal-mode diode to a picosecond pulse train. The repetition-rate of this laser source can be continuously and flexibly tuned from 1 GHz up to 6 GHz by simply changing the RF signal. We achieved a shortest pulse width of ~60 ps and a high SNR of > 75 dB at an operating frequency of 6 GHz. The simplicity and robustness of such a picosecond laser as well as the ability to synchronize with an external trigger make it a highly useful source for 2 μm high speed optical data processing, communications and metrology.**

Index Terms—**High repetition-rate laser, Tunable fiber laser, Phase modulation, Pulsed fiber laser.**

I. INTRODUCTION

Ultrafast lasers operating in the 2 μm spectral region have in recent years undergone rapid developments as driven by a number of potential applications. In particular, lasers based on a fiber format are increasingly desirable as they offer excellent beam quality, compact footprint, broad emission bandwidth and efficient power scaling. Thus far, pulse duration as short as 50 fs has been achieved through extra-cavity techniques [1, 2]. An ultra-broad tuning range of 200 nm was achieved in a nanotube mode-locked ring cavity laser, where a grating mirror is used for wavelength selection [3]. The output power up to 240 watts with picosecond pulse durations has been demonstrated by combining a picosecond fiber oscillator and a three stage thulium-doped amplifier [4]. Despite the impressive advancement, 2 μm pulsed lasers are still lacking behind in the area of repetition-rate scaling compared to its 1.5 μm counterpart [5-9]. Such multi-gigahertz repetition-rate is essential for novel 2 μm telecommunication and data processing systems, as well as for sensing and metrology [10-14].

High repetition-rate pulsed lasers can be realized through active or passive mode-locking, or via extra-cavity modulation techniques. 2 μm picosecond passively mode-locked pulses are being investigated by using SESAMs or nonlinear polarization rotation (NPE) [2]. Passive mode-locking represents a superior method for enabling extremely short pulses [15, 16], but the repetition-rate of passively mode-locked lasers is often limited within hundreds of MHz due to the relatively long cavity lengths for fiber lasers [17]. Engineering high repetition-rate passively mode-locked fiber lasers using highly-doped gain fiber and carbon-based saturable absorbers have achieved remarkable progress, but this has not been achieved in the 2 μm range yet [7, 18-22]. On the other hand, active mode-locking is more applicable for achieving high repetition ultrafast source [23-25]. Although tens of GHz have been reported at a wavelength of 1.5 μm [8], to the best of our knowledge, the highest repetition-rate of 2 μm actively mode-locked lasers is limited to ~1.5 GHz [9], limiting its application in high speed communication and data processing. In addition, in strict terms, it is not possible to achieve continuous repetition-rate tuning as the modulation frequency has to be an integral multiple of the cavity frequency. Howe et al. reported an impressive 18 GHz repetition-rate source at 2 μm by using two phase modulators as time-lens. However, the system exhibited relatively poor stability, low SNR and imperfect parabolic phase [26].

Spectrally masked phase modulation (SMPM) is another powerful extra-cavity technique to obtain high repetition (tens of GHz) pulse trains. In particular, compared with other amplitude modulation techniques, this modulation technique does not require a resonant cavity or DC bias [27], resulting in a number of advantages such as robustness of operation and ease of repetition scaling. 10-20 GHz SMPM systems have already been demonstrated at 1 and 1.5 μm [27, 28]. In this paper, drawing on recent technical advances of 2 μm fiber-optic devices, we have for the first time developed a high repetition, all-fiber laser source by SMPM, with a repetition-rate tunable up to 6 GHz. Our results pave the way for 2 μm high speed optical data processing, communications and metrology.

II. EXPERIMENTAL SETUP AND RESULT

SMPM is a simple and relatively inexpensive method for the generation of high-repetition-rate trains and it was first described by P. V. Mamyshev in 1994 [29]. The underlying mechanism for CW-to-pulse conversion in SMPM can be found in Ref. 29. A time varying sinusoidal phase shift, $\Delta\varphi$ is

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applied to a CW signal, which is achieved through the use of a lithium niobate phase modulator (LNPM) causing a cosinusoidal instantaneous shift to the optical frequency, due to the relationship between the phase shift Δφ and the optical frequency shift Δω, $\Delta\omega=\partial\Phi/\partial t$. Applying a spectral mask (i.e. a bandpass filter) to suppress most frequency but select only the regions of extreme frequency deviation, would result in a train of short pulses with a repetition-rate equal to the frequency of the initial sinusoidal phase modulation. Furthermore, as only the extreme edges of the sinusoid are being selected, there is minimal optical frequency deviation, and so the chirp on the generated pulses will be low. Since SMPM directly modulates the phase of lightwave, there is no need for a DC bias [27, 28].

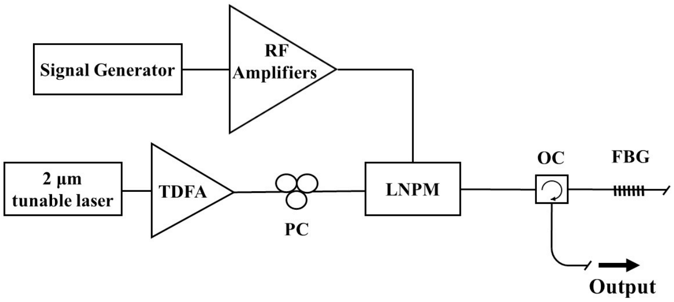

Fig. 1. Schematic setup of the SMPM system. TDFA: thulium-doped fiber amplifier; PC: polarization controller; LNPM: lithium niobate phase modulator; OC: optical circulator; FBG: fiber Bragg grating.

As shown in Fig. 1, the experimental setup is composed of a RF electric driving circuit and an optical circuit. RF driving source (up to 10 GHz) is provided by a signal generator (KEYSIGHT N5183) and the signal is then amplified by a RF amplifier (SHF 81) to an output power of 26 dBm. For the optical part, a 2 µm CW diode laser (Eblana Inc.) whose wavelength can be fine controlled by temperature is used as the seed source. To compensate for the insertion loss, the laser is then fed to a thulium-doped fiber amplifier (NPI Lasers Inc.) and amplified to an output power of ~80 mW. Subsequently, a polarization-sensitive lithium niobate phase modulator (LNPM, EOSPACE Inc.) is used for sideband generation. To achieve maximum transmission and to optimize the condition for sideband generation, a polarization controller is employed after the thulium amplifier. Then, an optical circulator and a FBG with a pass bandwidth of 0.8 nm are used to extract a portion of the modulated laser (with broadened spectra) for further optical diagnosis.

In previous SMPM systems, a tunable filter is usually used to align with the sidebands of the broadened spectra after phase modulation. Instead of using a tunable filter which is not widely commercially available at 2 µm, here we combine a fixed passband FBG with a temperature tunable seed source. Fig. 2 shows the red-shift of the operating wavelength of the diode as the temperature increases. A maximum wavelength shift of 0.33 nm is obtained for a temperature shift of 3℃, as measured by an optical spectrum analyzer (Yokogawa AQ6375).

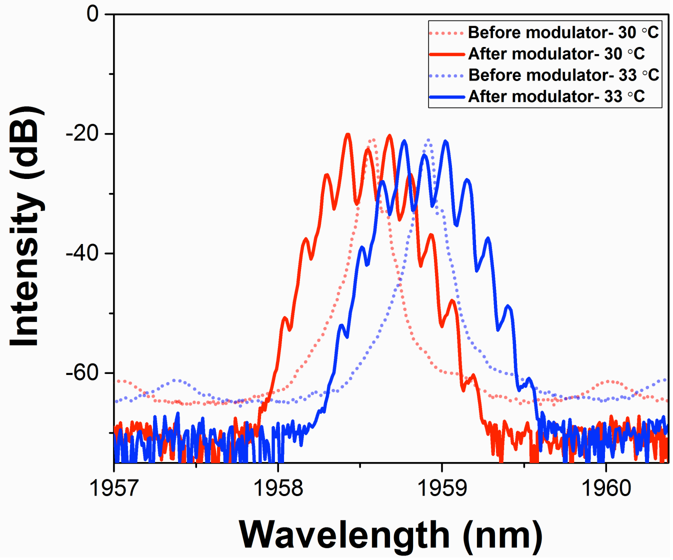

Fig. 2. Optical spectra of the initial diode and after phase modulated at different diode temperature.

Fig. 3 shows the optical spectra of the source (operating at 6 GHz) before and after the FBG. It can be seen that phase modulation produces a comb of new frequency components located on both sides of the center wavelength (~1958.7 nm). The measured passband of the FBG, with a center wavelength of 1959.6 nm, is also plotted. After the FBG, the short-wavelength portion of the spectrum is seen to be effectively suppressed, which is crucial for obtaining higher SNR of SMPM generated pulses. The interval between the new frequency components is the same as that of the driving electrical signal. As the frequency of electrical signal is increased, the number of new frequency components contained in the sideband decreases. We note that an effective bandwidth of ~ 0.3 nm (at -10 dB) is achieved for our system (marked by the dotted square in Fig.3). It is estimated that about 23, 12, and 4 side modes participate in the pulse forming process, for 1, 2 and 6 GHz. This sets the upper limit for the operating frequency, as a good number of side modes would guarantee high quality pulse forming through in-phase interference [27, 28].

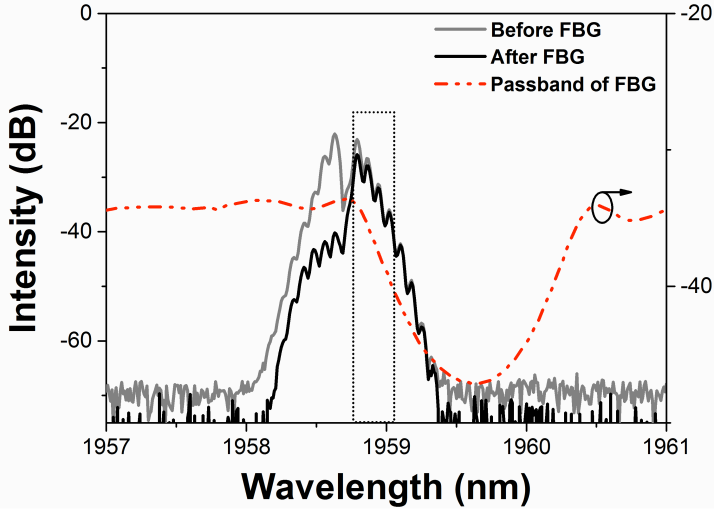

Fig. 3. Optical spectra of phase modulated output before (grey) and after (black) the FBG, at an operating frequency of 6 GHz. Dash-dotted line indicates the passband of the FBG.

The output is detected by a high speed photodetector with a nominal bandwidth of 11 GHz (EOT ET-5000F), which is then analyzed by a 13 GHz real-time oscilloscope (KEYSIGHT DSA91304A). The output pulse train with varying repetition-rate (1 GHz, 2 GHz and 6 GHz) are clearly observed as shown in Fig. 4. The ratio of pulse width over the modulation period is ~ 1/8, 1/7, and 1/3, in agreement with the decreasing sideband number. It is clearly observed that more sideband modes result in a better duty cycle pulses. The pulse width achieved with the current setup is 125 ps, 65 ps and 60 ps for the repetition of 1 GHz, 2 GHz and 6 GHz, respectively. It is generally true that setting a higher repetition-rate will give narrower pulse width, similar to other SMPM reports [28, 29]. Overall, the 2 GHz pulse shows the best performance in terms of pulse quality, probably due to a good balance between effective sideband modes and the stronger spectral modulation at this frequency. Increasing the 3 dB bandwidth of the FBG or passband filter will make optimal results achieved at higher repetition-rates. The pulse at 6 GHz can be well fitted by a Gaussian pulse shape and the TBP of the pulse is ~ 0.45. Fig. 5 depicts the RF spectrum of the pulses at a center frequency of 6 GHz measured with a RBW of 300 Hz in the range of 300 MHz. A rather high signal to noise ratio of 75 dB indicates the good stability in this operation regime. We measured a timing jitter of ~4.2 ps (at 6 GHz modulation frequency), using the measurement kit of the KEYSIGHT oscilloscope, It is believed that further reducing the line-width of the diode can help enhance the overall stability, including timing jitter and intensity jitter of the system.

We further carried out a pulse generation experiment using a fast intensity modulator (EO Space). A comparison was made with respect to the SMPM technique. The temporal and RF spectrum are shown in Fig. 6, respectively. It is found that the pulses produced by the intensity modulator (IM) always take a sinusoidal shape, which makes it relatively broader than SMPM and more difficult for subsequent compression. In addition, at the same output power level, the IM pulses show poorer SNR than our SMPM pulses.

It should be noted that the incorporation of a tunable fiber laser as the seed in our experimental setup brings significant flexibility in the system and may be employed to enable a wavelength reconfigurable source (with the incorporation of a tunable filter). One advantage of this system is that the repetition-rate can be flexibly changed by modifying the driving RF signals. To obtain even shorter pulse width, we have attempted a frequency of 10 GHz. Due to the narrow bandwidth of the FBG, at such a high modulation frequency, the pulse waveforms approximate a sinusoidal shape, as only 1 or 2 sideband modes participating in the optical interference. In addition, the pulse amplitude shows appreciable fluctuations at 10 GHz. A number of factors may lead to such degradation, for example the non-ideal spectral profile of the FBG filter shape, as well as the inefficient sideband generation at 10 GHz by phase modulator with regard to the lower frequency cases (<6 GHz). Further experiments are underway for optimizing the system's performance, a tunable filter with broader bandwidth will be employed to replace the FBG, providing more flexibility for optimizing the system.

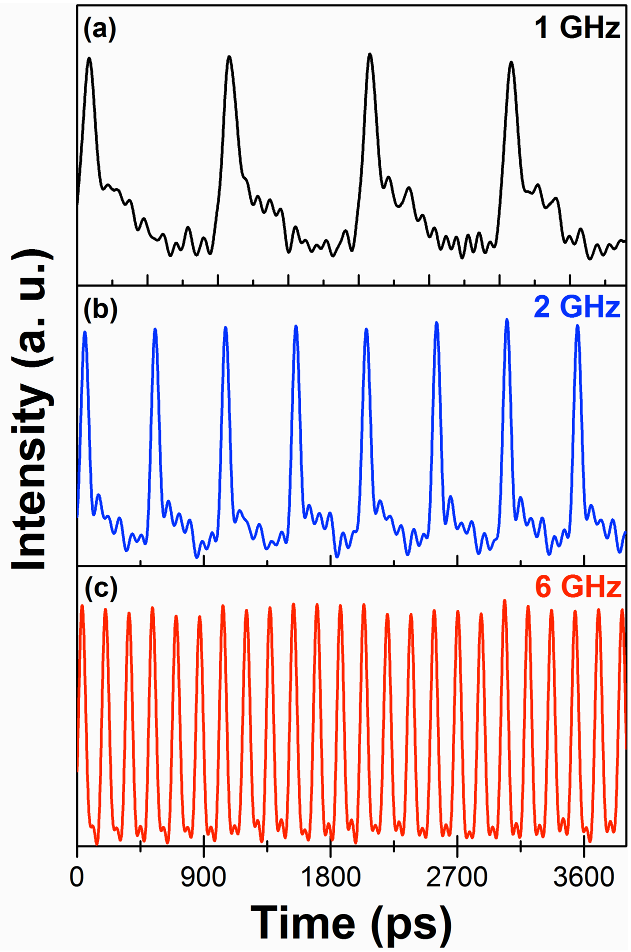

Fig. 4. The pulse trains observed by a digital signal analyzer, with repetition rates of (a) 1GHz, (b) 2 GHz and (c) 6 GHz.

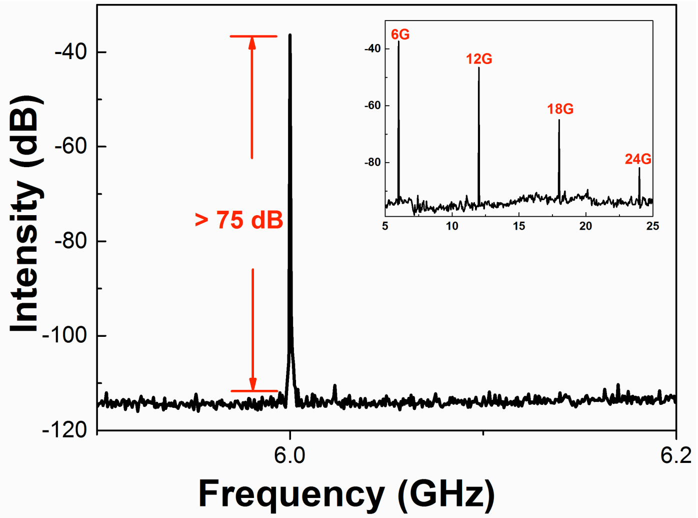

Fig. 5. The RF spectrum over a span of 300 MHz, RBW=300 Hz. Inset: RF spectra over a span of 20 GHz, RBW=30 kHz, showing harmonics components at 6G, 12G, 18G, 24GHz.

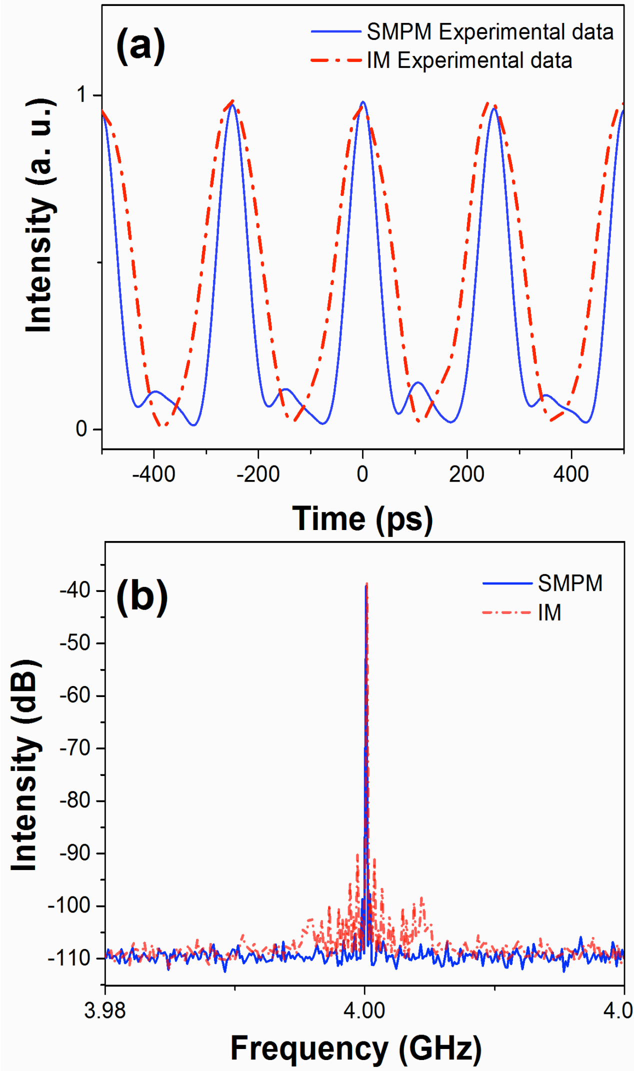

Fig. 6. (a) Temporal waveform and (b) RF spectrum for the SMPM and the fast intensity modulation methods.

III. Conclusion

In summary, we have for the first time demonstrated a stable and highly flexible GHz repetition-rate pulse sources at 2 µm, employing SMPM technique. A tunable seed diode laser and a FBG can be combined to yield effective pulse generation. By simply adjusting the modulation RF frequency, the repetition rate of the output pulses can be continuously and flexibly controlled from 1 GHz up to 6 GHz which shows great potential to high speed mid-infrared applications.

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