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Rapid, k-space linear wavelength scanning laser source based on recirculating frequency shifter

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Abstract: We propose and successfully demonstrate a k-space linear and self-clocked wavelength scanning fiber laser source based on recirculating frequency shifting (RFS). The RFS is realized with a high speed electro-optic dual parallel Mach-Zehnder modulator operating at the state of carrier suppressed single sideband modulation. A gated short pulse is injected into an amplified RFS loop to generate the wavelength scanning pulse train. We find that the accumulation of in-band amplified spontaneous emission (ASE) noise over multiple scanning periods will saturate the erbium-doped fiber amplifier and impede the amplification to the pulse signal in the RFS loop. To overcome the degradation of temporal signal due to the accumulation of ASE noise over multiple scanning periods, we insert a modulated optical switch into the RFS loop to completely attenuate the in-band ASE noise at the end of each scanning period. The signal to noise ratio of the temporal pulsed signal is greatly enhanced. K-space linear and self-clocked wavelength scanning fiber laser sources in 6.1 nm/7.2 nm scanning range with 20 GHz/30 GHz frequency shifting are successfully demonstrated.

OCIS codes: (140.3510) Lasers, fiber; (130.4110) Modulators; (130.7405) Wavelength conversion devices.

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1. Introduction

Wavelength-swept fiber lasers have attracted much interest due to its wide potential applications in optical coherence tomography (OCT), distributed fiber sensing based on optical frequency domain reflection (OFDR) technique, continuous wave terahertz generation, and optical communication systems. To generate wavelength swept signals in fiber lasers, different techniques have been proposed [1–15]. The most straightforward realization of swept laser consists of a broadband gain medium with a tunable optical bandpass filter in the cavity [1,2]. The transient passband of the tunable filter will set up a narrow transparent window on the spectrum inside which signals can be amplified in the cavity. To allow the building up of laser signal at the defined wavelength from spontaneous emission inside the cavity, the transparent window should open within a sufficient long time which is at least several hundred times of the optical round trip time in the cavity. The long build-up time of the signal intrinsically limits the maximum sweep rate of the laser and also results in low power, and broad instantaneous linewidth [2,3]. To circumvent the long build-up time of laser signals, Fourier domain mode-locking (FDML) technique was proposed, where the scan frequency of the tunable filter is matched to the optical round trip time in a long fiber cavity [4,5]. By using the FDML scheme, sweep rate has been improved significantly [6,7]. However, the coherence length of standard FDML laser is limited by the bandwidth of the fiber Fabry-Pérot tunable filter (FFP-TF). Another disadvantage of FDML laser is the nonlinear sweeping trace of the optical frequency versus time which requires resample and remap of the detected fringe signals in OCT systems. With short fiber cavities, dispersion tuning or dispersion mode-locking techniques have also been demonstrated with wide sweeping ranges and scanning speed up to 400 kHz, benefiting from the tunable-filter-free configuration [8–10]. However, with the increasing of sweep rate, the instantaneous linewidth of the laser signal will be broadened and the coherence length will decrease accordingly. Furthermore, additional techniques should be adopted to convert the bidirectional frequency scanning in the above two schemes to practical unidirectional scanning in applications such as

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OCT [11,12]. Other methods based on time-division-multiplexing of ultra-short pulses with broad spectrum by incorporation of dispersion within the cavity or outside the laser sources were also reported [13–15]. But the sweeping rate is not adjustable once the dispersive medium is chosen and deployed in the system.

To enhance the roll off length of sensitivity and the ranging depth in OCT imaging systems, light sources with discrete frequency steps and narrow instantaneous bandwidth have been demonstrated [16–18]. Different to the continuous and smooth frequency sweeping in the above schemes, the frequency sweeping is discretized into multiple small sections by a spectral comb filter. The instantaneous linewidth of the signal can be reduced in the small sections because of the confinement of the comb filter, which can enhance the sensitivity of OCT over a long ranging depth. However, the enhanced ranging depth is still at centimeter level which is much shorter than the kilometer level coherence length of the signals coming from most commercial available single frequency lasers such as DFB lasers.

Besides the gradually growing of laser signals from spontaneous emission in filter-guided laser cavities, wavelength conversion is an alternative method to obtain multiple wavelength coherent laser signals. Benefiting from the rapid development of optical components in communications, nowadays, we can transfer a laser signal to another wavelength which can be several tens of gigahertz far from the original wavelength with the mature single-side-band (SSB) modulation technique. Especially when the SSB modulation is cascaded by circulating the signal in an amplified fiber loop, optical frequency comb (OFC) extended to THz bandwidth can be generated from the seeding continuous wave signal after several ten times of propagation in the recirculating frequency shifter (RFS) [19,20]. Since the generated signals at new wavelengths have almost same linewidth to the seeding continuous wave, the coherence length of the new signals can be very long. Recently, Lei *et al.* have successfully demonstrated a wavelength swept source based on RFS seeded by a gated light [21,22] but not a continuous wave. In experiment, the gated signal with duration almost same to the round trip time of the RFS loop was repeatedly shifted to generate a wavelength stepped output. In the reported system, although a flat spectrum is obtained in experiment, the temporal signal, which is very important for wavelength swept lasers when they are used in applications such as OCT, is not characterized.

In this paper, we propose and demonstrate a rapid, k-space linear and self-clocked wavelength scanning fiber laser source based on RFS. The output signals with different wavelengths will be well separated in time domain and the pulses can be directly used as clock signal to trigger the sampling of signals at different wavelengths. Different from the reported OFC generation configurations, we will use a short pulsed input to generate a pulsed wavelength scanning laser output. In order to realize a self-clocked wavelength scanning output, we insert an optical switch into the RFS loop to limit the accumulation of in-band ASE noise. In Section 2, we will introduce the experimental setup and the operation principle of the wavelength scanning source. The experimental results will be shown and discussed in Section 3. Conclusions will be drawn in Section 4.

2. Experimental setup and operation principle

Figure 1 shows the schematic diagram of the proposed wavelength scanning fiber laser source based on RFS. The laser source is composed of a tunable laser (TL), an optical switch-1, a polarization controller (PC-1) and a RFS. The RFS is a closed fiber loop, which consists of a 3dB coupler, an optical isolator, an electro-optic dual parallel Mach-Zehnder modulator (DPMZM), an erbium-doped fiber amplifier (EDFA), an optical switch-2, a tunable band-pass filter (BPF) and a PC-2.

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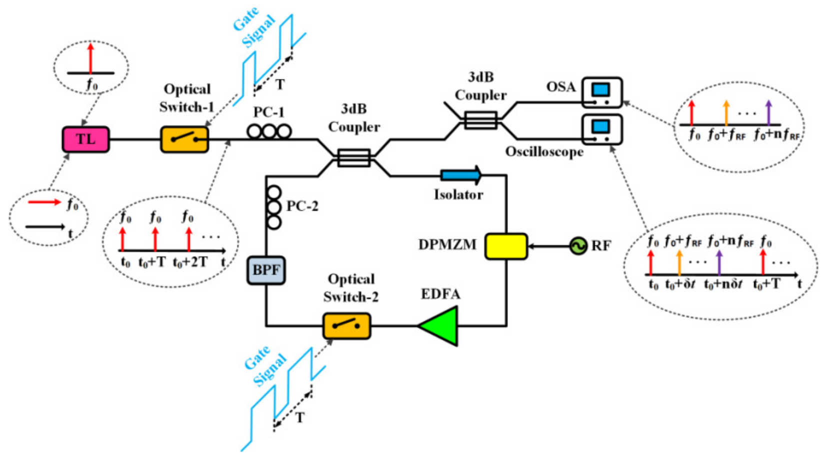

Fig. 1. Schematic diagram of wavelength-stepped fiber laser source based on RFS.

The tunable laser is used as a seed source which has a maximum output power of 16 dBm and a linewidth of <100 kHz. The optical switch-1 modulates the continuous wave optical signal into periodic pulse train before it is launched into the RFS through the 3dB coupler. The seed light injected into the RFS loop will be modulated by the DPMZM which was operated under CS-SSB modulation state. The spectrum of the optical signal will be shifted by a frequency determined by the driving signal of the modulator. The EDFA is used to compensate the loss introduced by the CS-SSB modulator, coupler and other components in the loop. Since the DPMZM is a polarization dependent modulator, we use two polarization controllers PC-1 and PC-2 to adjust the polarization states of the light. The optical isolator is used to ensure the unidirectional propagation of the light in the loop. Then, part of the frequency shifted light will be coupled out of the loop by the coupler and the residual part will be injected into the RFS for next round trip propagation. This process will repeat consecutively and a series of optical pulses with identical frequency and temporal separations will output from the loop one by one. In the RFS loop, a tunable band-pass filter is used to limit the number of circulations of the seed light in the loop.

In an ideal case that the amplified spontaneous emission (ASE) noise from the amplifier is not considered and the amplifier will compensate the cavity loss in every round trip, the RFS loop should emit a series of identical pulses same to the seed pulse. In frequency domain, the spectrum should be a series of equally spaced comb lines with an envelope defined by the tunable bandpass filter. When the CS-SSB modulator is driven by a sinusoidal electric signal with frequency δf, the frequency spacing of signals from adjacent round trips is fixed to δf. The time delay between adjacent pulses is determined by the RFS loop as $\delta t = nL/c$, where n is the refractive index, c is the speed of light in vacuum, and L is the optical length of the RFS loop. The wavelength stepped source is hence linear in k-space with a slope $\delta f/\delta t$. In experiments, the periodic pulse train can be used as the clock signal straightforwardly to indicate the sampling of signals with different wavelengths. The repetition rate of the swept source is determined by the repetition rate of the driving signal applied on the optical switch-1. In each period of wavelength scanning, the number of pulses with identical delay δt and different wavelengths is determined by the bandwidth $\Omega$of the tunable bandpass filter as $\Omega/\delta f$.

Clearly, the performance of the wavelength scanning source will be affected when the noise of amplifier is considered. As a matter of fact, the noise problem is the dominant bottleneck that limits the performance of such RFS based sources. In each round trip, the signal will pass through the EDFA once where the signal to noise ratio will be decreased because of the ASE noise. The tunable bandpass filter in the cavity will suppress the ASE noise outside the spectral window in each round trip but it cannot affect the ASE noise inside

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the window. Thus the in-band ASE noise will continuously accumulate despite of the periodic growing and vanishing of the signal in each scanning period. The accumulation of noise will severely degrade the temporal performance of the scanning source. To solve this problem, we propose to insert another optical switch-2 into the RFS loop to cut down all of the signals including the ASE noise at the end of each scanning period. When the wavelength of signal is shifted outside the spectral window of the tunable bandpass filter, we can turn off the optical switch-2 for a few round trips of the RFS loop to suppress the ASE noise completely before the staring of next scanning period. In the next scanning period, the new generated ASE noise will be much lower than the accumulated noise without the optical switch-2. Thus the signal to noise ratio of the output waveform can be enhanced.

3. Experimental results and discussion

To validate the wavelength scanning source design and confirm the analysis in Section 2, we conduct the experiment with the configuration shown in Fig. 1.

Before the integration of the system, the performance of the CS-SSB based on the DPMZM is characterized first. The continuous wave from the tunable laser with a wavelength λ_0 = 1560 nm is injected into the DPMZM, which is driven by a 20 GHz single frequency RF signal. The bias voltages of the DPMZM are stabilized by an automatic bias controller to optimize the CS-SSB modulation performance. The optical spectra of the signals before and after the CS-SSB modulation are shown in Fig. 2. The signal at 1560 nm is shifted by 20 GHz to about 1559.84 nm when it passes through the DPMZM. The carrier signal and higher order sidebands are suppressed by more than 30 dB when comparing to the shifted signal.

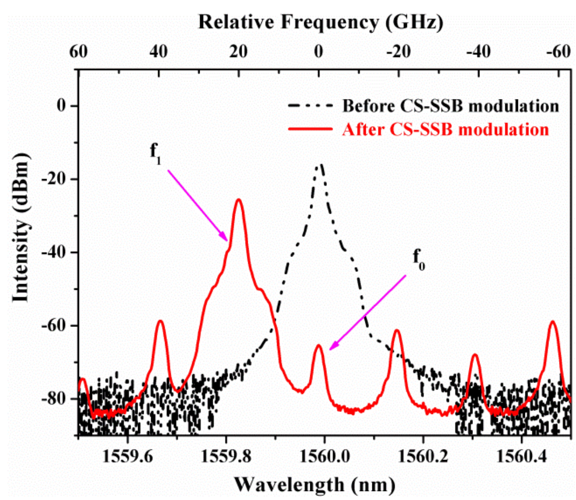

Fig. 2. The spectra before and after the CS-SSB modulation.

Then the DPMZM is applied into the RFS loop as described in Fig. 1 but without the optical switch-2. A wavelength scanning source with 32 wavelengths is obtained. To obtain a self-clocked wavelength scanning source, the duration of the input seed pulse is set to 10 ns, which is much shorter than the round trip time of the RFS loop. It should be noted that the system performance is not sensitive to the choice of the pulse duration. The choice of this pulse duration depends mostly on the requirements of the applications and the response time of the optical switch-1. The output spectrum and waveform are shown in Figs. 3(a) and 3(b) respectively. The wavelength scanning starts from wavelength 1560 nm, which is determined by the tunable laser, and ends at 1554.88 nm, by setting the bandwidth of the optical band-pass filter to 5.12 nm (1554.88 nm-1560 nm). With 20 GHz or 0.16 nm spacing, the signal passes through the RFS loop for 32 round trips before it exits the passband of the tunable filter. The RFS loop has a round trip time about 230 ns and the repetition rate of optical

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switch-1 is set to 100 kHz to avoid overlap of the signals in adjacent scanning periods. From Fig. 3, although the envelope of the spectrum is flat and the signal to noise ratio observed on the spectrum is relative high, but the output waveform of the wavelength scanning source is unsatisfactory as shown in Fig. 3(b). The pulse signal injected into the RFS loop decreases rapidly and it is totally overwhelmed by the noise after circulating about 20 times in the RFS loop. Such degradation of the signal should be induced by the accumulated ASE noise in the cavity. From Fig. 3(b), the pulse signal has not obtained enough gain to compensate the loss in the RFS loop. Since the power of the pulse signal is still far below the saturation power of the EDFA, the EDFA should have been saturated by the accumulated ASE noise because the noise can circulate and get amplified in the loop endlessly.

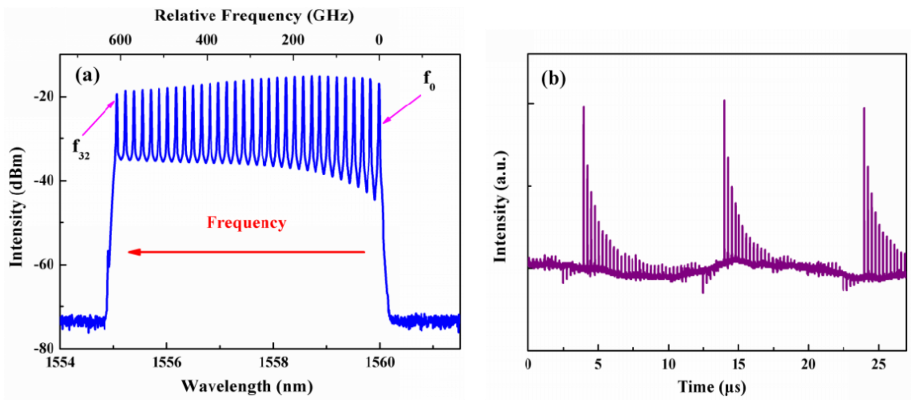

Fig. 3. (a) The spectrum and (b) waveform of the wavelength scanning source without the optical switch-2. The scanning range is 5.12 nm and the wavelength spacing is 0.16 nm. The wavelength scanning starts from 1560 nm and ends at 1554.88 nm.

From the observation and analysis, the accumulating ASE noise in the RFS loop not only decreases the signal to noise ratio, but also saturates the EDFA which impedes the amplification of the pulse signal to compensate the loop loss. To obtain a wavelength scanning source with acceptable temporal performance, the accumulation of ASE noise in the RFS loop should be avoided first.

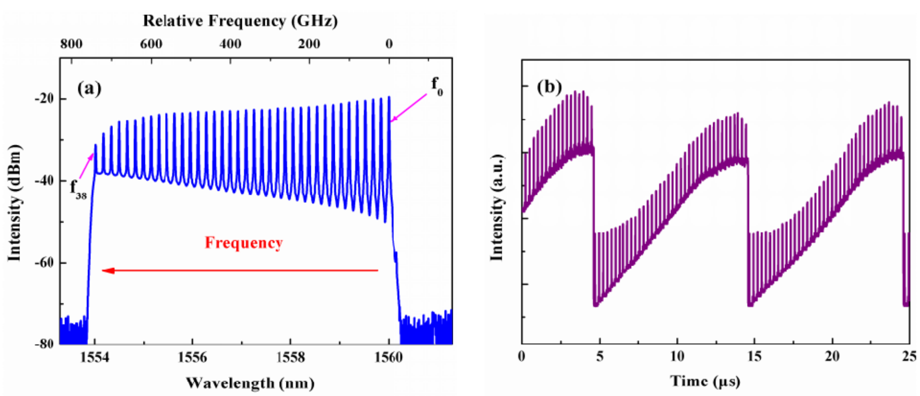

Fig. 4. (a) The spectrum and (b) waveform of the wavelength scanning output with the optical switch-2. The scanning range is 6.1 nm and the wavelength spacing is 0.16 nm. The wavelength scanning starts from 1560 nm and ends at 1553.9 nm.

The optical switch-2, which is a modulated semiconductor optical amplifier (SOA) in experiment, is then inserted into the RFS loop as the schematic shown in Fig. 1. Using an SOA provides extra gain to the system to compensate for the insertion loss of the optical elements and other linear loss in the system. The round trip time of the RFS loop is slightly increased to 240 ns. In the 10 μs period of the scanning, the signal can circulate in the RFS for 41 times at most. In experiment, we set the bandwidth of the tunable filter to 6.1 nm (1553.9 nm-1560 nm), which allow 38 times of 20 GHz frequency shifting of the signal in the RFS loop. The scanning signal has a duration of 9.12 μs. To be accordant to the filter limitation, we switch off the SOA immediately when the signal exits the passband of the filter and the off state will last 0.88 μs, which is more than 3 round trips of the RFS loop, to suppress the ASE noise. From the results shown in Fig. 4, the spectrum has a comparable flatness and a slight larger signal to noise ratio than the spectrum shown in Fig. 3(a), but the waveform has a much better performance than that shown in Fig. 3(b). The amplitude of the pulse signal increases continuously besides the simultaneous increasing of the noise floor. However, the pulse signal is always clearly shown on the waveform in the whole wavelength scanning period. Obviously, the gain saturation caused by the accumulated ASE noise has been successfully avoided by the modulated optical switch-2.

When the gain saturation of the EDFA is avoided, the dominant issue that limits the signal performance of the wavelength scanning source will be the ASE noise accumulated in each single scanning period. As shown in Fig. 4(b), the noise floor will increase greatly accompanying the amplification of the pulse signal. To improve the signal to noise ratio, the number of circulations in the RFS loop should be controlled to be small and the ASE noise should be completely attenuated before the starting of a new scanning period.

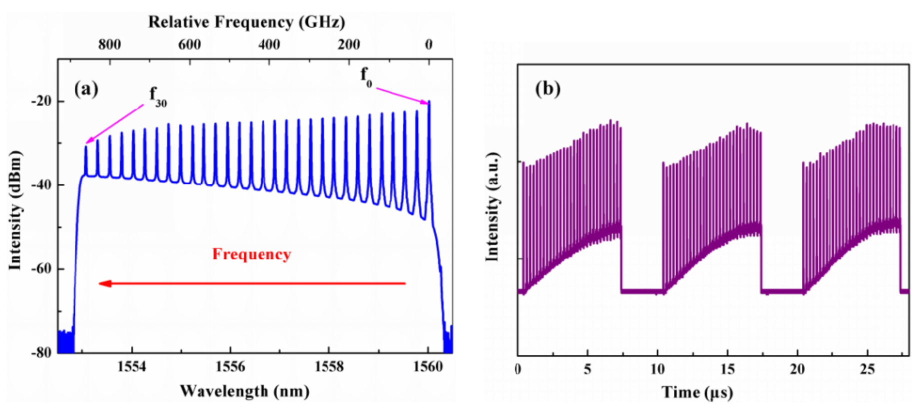

Fig. 5. (a) The spectrum and (b) waveform of the wavelength scanning output with a longer off time of the optical switch-2. The scanning range is 7.2 nm and the wavelength spacing is 0.24 nm. The wavelength scanning starts from 1560 nm and ends at 1552.8 nm.

To obtain a large wavelength scanning range with limited round trips in the RFS loop, we increase the frequency of the driving signal of the modulator to 30 GHz and the corresponding wavelength spacing will be 0.24 nm. Along such arrangement, a scanning range of 7.2 nm (1552.8 nm-1560 nm) can be obtained in just 30 round trips. The scanning signal duration is reduced to 7.2 μs and the SOA is turned off in the residual 2.8 μs in the scanning period to completely suppress the ASE noise. The output spectrum and waveform are shown in Figs. 5(a) and 5(b) respectively. The spectrum has a similar envelope and signal to noise but a larger wavelength spacing 0.24 nm when comparing to the spectrum shown in Fig. 4(a). With a longer off time of the optical switch-2, the attenuation of the ASE noise is more complete thus the signal to noise ratio on the waveform is obviously improved. The growing of the noise floor is also weakened benefiting from less circulating number in the RFS loop.

From Fig. 5, although an increasing noise floor is still unavoidable on the waveform, but the temporal signal is already good enough to be used as a clock signal with acceptable signal to noise ratio. Such performance enhancement comparing to that in Fig. 3 is benefiting from the ASE noise attenuation by the modulated optical switch-2. Note that the time interval between adjacent pulses can be reduced by shortening the length of the RFS loop to increase the scanning rate. Wavelength scanning source with repetition rate of ~MHz can be obtained if the length of the RFS loop is shortened to the level of a few meters. Since the accumulation of ASE in the system depends on the number of times the signal passes through the amplifier but not the loop length, the system performance will remain the same even when the fiber loop length is reduced. We should also note that the wavelength sweeping direction can be reversed if the bias voltages of the DPMZM are changed to induce a negative frequency shift to the input optical signal.

4. Conclusions

In this paper, we have proposed and successfully demonstrated a self-clocked wavelength scanning fiber laser source based on a recirculating frequency shifter to generate linearly wavelength-stepped output. In the system without optical switch in the RFS loop, the accumulated ASE noise will eventually saturate the EDFA and impede the amplification to the seed pulse signal. To generate temporal pulsed signals with high signal to noise ratio, an optical switch is introduced into the RFS loop to attenuate the accumulated in-band ASE noise in each scanning period. Wavelength scanning output with a wavelength spacing of 20 GHz in a 6.1 nm sweeping range is achieved. The injected pulse seed is effectively amplified in the RFS loop. The performance of the temporal signal is further enhanced by increasing the frequency shifting to 30 GHz. A self-clocked wavelength scanning source with a 7.2 nm sweeping range and high signal to noise ratio on the waveform is obtained. Such self-clocked wavelength scanning sources with high signal to noise ratio on both the spectrum and waveform will have potential applications in high resolution optical frequency domain ranging and imaging systems.

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