Tunable Optoelectronic Oscillator Incorporating a High-Q Spectrum-Sliced Photonic Microwave Transversal Filter

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***Abstract*— A tunable optoelectronic oscillator implemented employing a high-Q-factor spectrum-sliced photonic microwave transversal filter without using any electronic microwave filters is proposed and experimentally demonstrated for the first time to our knowledge. The high-Q-factor photonic microwave transversal filter is implemented using a sliced broadband optical source and a dispersive element, to perform frequency-tunable microwave frequency selection. The central frequency of the microwave filter is a function of the wavelength spacing of the sliced optical source and the chromatic dispersion of the dispersive element. Therefore, the oscillation frequency can be tuned by changing either the channel spacing of the sliced broadband optical source or the chromatic dispersion of the dispersive element. A proof-of-concept experiment is performed. An optoelectronic oscillator with a tunable frequency range of 9.7 GHz is achieved. The generated microwave signal exhibited a good phase noise performance with a phase noise of –120 dBc/Hz at an offset of 10 kHz.**

***Index Terms*— Microwave generation, microwave photonics, optoelectronic oscillator, transversal filter.**

I. Introduction

An OPTOELECTRONIC oscillator (OEO) [1] with a largely tunable frequency range has attracted great interests recently thanks to its numerous potential applications such as in wireless communications, optical signal processing [2]–[4], radar, and modern instrumentation [5]. In general, the oscillation modes of an OEO are densely spaced due to the long loop length ranging from a few meters to tens of kilometers. To ensure an OEO to operate at a single oscillation mode, a high-Q microwave filter is usually needed to perform the mode selection [6], [7]. To reduce the requirement for a high Q-factor microwave filter, schemes employing multiple loops have been proposed to increase the oscillation mode spacing. However, an OEO with multiple loops would have a poorer system stability and higher system cost. More importantly, the OEO becomes more complicated to achieve frequency tuning and the frequency tunable range is very limited [8].

In recent years, photonic microwave filters have been used to overcome the limitations of pure electronic microwave filters and bring supplementary advantages inherent to photonics such as low loss, high bandwidth, immunity to electromagnetic interference (EMI), large tunability, and high reconfigurability. An important research topic in the field of photonic microwave filters is to increase the Q factor [9]–[11]. To implement a high-Q photonic microwave filter, a large number of taps is generally required. A low-cost solution is to use a broadband spectrum from an erbium-doped fiber amplifier (EDFA) or a superluminescent light-emitting diode (SLED), which is sliced by a multichannel filter to form a finite impulse response (FIR) filter with the number of taps identical to the number of the channels, to achieve a desired Q factor [10].

Recently, we have proposed an approach to achieving a frequency-tunable OEO using a photonic microwave transversal filter [12]. Some preliminary results have been obtained. Although photonic microwave filters based on a spectrum-sliced light source have been widely investigated, it is the first time to implement an all-optical tunable OEO based on a spectrum-sliced photonic microwave filter. Due to the high Q factor of the spectrum-sliced photonic microwave transversal filter, the entire OEO loop has a frequency response corresponding to the photonic microwave filter to support only single-frequency oscillation. The multichannel filter in this system is a programmable optical filter with tunable channel spacing. Therefore, the photonic microwave filter is tunable, leading to the tuning of the oscillation frequency. An experiment is performed. An OEO with its frequency tunable over a range as large as 9.7 GHz is achieved. The generated microwave signal exhibited a good phase noise performance with a phase noise of -120 dBc/Hz at an offset of 10 kHz. The key significance of the proposed technique is that no electronic microwave filters are needed which ensures a large frequency tunable range with all-optical tuning.

II. Principle

The schematic of the proposed frequency-tunable OEO is shown in Fig. 1. A broadband amplified spontaneous emission (ASE) light source is coupled to a programmable multichannel optical filter, which is employed to slice the broadband spectrum into multiple channels. The spectrum-sliced broadband source is then fiber coupled into a Mach–Zehnder modulator (MZM), which is biased at the quadrature point. The MZM is connected to a dispersive element which can be a dispersion-compensating fiber (DCF), a single-mode fiber (SMF) or a

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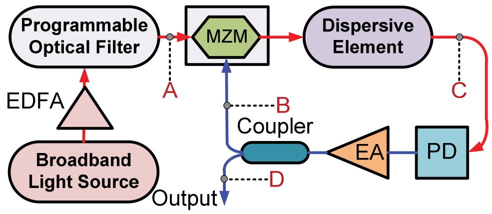

Fig. 1. Schematic diagram of the proposed frequency-tunable optoelectronic oscillator. MZM: Mach–Zehnder modulator. PD: photodetector. EA: electrical amplifier. EDFA: erbium-doped fiber amplifier.

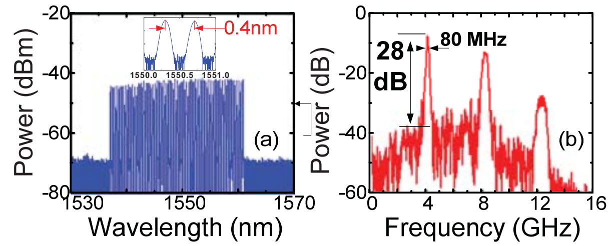

Fig. 2. (a) Measured optical spectrum of the spectrum-sliced broadband source. Inset: zoomed-in view of the sliced spectrum. (b) Measured frequency response of the photonic microwave transversal filter. Inset: zoomed-in view of the first-order resonance response.

linearly chirped fiber Bragg grating (LCFBG). The optical output from the dispersive element is converted to an electrical signal at a photodetector (PD) and then fed back to the MZM to form the OEO loop. An electrical amplifier (EA) is used in the loop to provide sufficient electrical gain.

To study the open-loop response of the OEO, we assume that the loop is opened at point B in Fig. 1 and the MZM is driven by an electrical signal with a frequency of f_m. The microwave-modulated optical signal is then directed into the dispersive element. The spectrum-sliced optical source, the MZM and the dispersive element effectively form a high-Q photonic microwave transversal filter, which functions to perform microwave frequency selection.

It is known that a FIR filter has a periodic spectral response with adjacent channels separated by a free spectral range (FSR). The resonance frequency of the microwave transversal filter at the nth channel is given by [13]

$$f_n = \frac{n}{\Delta\lambda \times \chi} \tag{1}$$

where n is an integer which denotes the order of the resonance frequency, $\Delta\lambda$ is the channel spacing of the sliced optical spectrum, χ denotes the dispersion value of the dispersive element. It is worth noting that the peaks at the higher order resonance frequencies are effectively suppressed due to the wide linewidth of a single channel of the sliced spectrum [9]. By tuning the linewidth of the sliced spectrum, the suppression ratio of the generated high-order harmonics can be changed. Therefore, the peak at the first-order ($n = 1$) resonance frequency will be much greater than those at the other higher order resonance frequencies. It can be seen from (1) that the first-order resonance frequency can be tuned by changing the channel spacing or the dispersion of the dispersive element. When the photonic microwave transversal filter is incorporated in the proposed OEO, a microwave signal only at the first-order resonance frequency will have the highest gain and be generated. Again based on (1), the frequency of the microwave signal from the OEO can be tunable by changing the channel spacing of the sliced spectrum or the dispersion of the dispersive element.

III. Proof-of-Concept Experiment and Discussion

An experiment is performed based on the setup shown in Fig. 1. An ASE optical source is first amplified by an EDFA to increase its power. The spectrum of the broadband optical source is then sliced by a programmable optical filter (Finisar WaveShaper 4000S). The programmable optical filter has a minimum filter bandwidth of 10 GHz and a maximum filter bandwidth of 5 THz. The spectrum-sliced broadband optical source is directed into a 20-GHz MZM. The modulated optical signal is then directed into a DCF and converted to an electrical signal at a 25 GHz PD. An EA with a bandwidth covering from 3 GHz to 18 GHz is used to provide a sufficiently large electrical gain in the OEO loop. The electrical spectrum of the generated microwave signal is measured by an electrical spectrum analyzer (ESA, Agilent E4448A).

In the experiment, a DCF with a dispersion value of 609 ps/nm functions as the dispersive element is used. The sliced spectrum of the broadband light source is given in Fig. 2(a). The inset shows a zoom-in view of the sliced spectrum. The broadband ASE light source is sliced into 60 channels with a channel spacing of 0.4 nm. Based on (1), the first-order resonance frequency of the photonic microwave filter is calculated to be 4.1 GHz. Note that the EA employed in the loop only has a bandwidth from 3 to 18 GHz, the baseband resonance is not amplified and cannot be seen in Fig. 2(b).

The frequency response of the photonic microwave transversal filter is measured. To do so, the loop of the OEO is opened at the output port of the EA, and the frequency response is measured using a vector network analyzer (Agilent E8364A). Fig. 2(b) shows the measured frequency response of the photonic microwave transversal filter. A zoom-in view of the first-order resonance response is also shown in Fig. 2(b). The 3-dB bandwidth of the first-order resonance is 80 MHz. The FSR of the photonic microwave transversal filter is 4.09 GHz. Thus, the Q factor of the microwave filter is calculated to be about 51. The first resonance frequency is 4.09 GHz which agrees well with the theoretical value of 4.1 GHz. It is also worth noting that the higher order resonances are effectively suppressed due to the wide linewidth (3-dB bandwidth: 0.08 nm) of the sliced spectrum of each channel. The extinction ratio of the photonic microwave transversal filter is more than 28 dB, which is large enough to suppress the undesirable eigenmodes in the OEO. Then, the OEO loop is closed. Oscillation starts, and a microwave signal is generated. Fig. 3(a) shows the spectrum of the generated 4.09 GHz signal. The inset in Fig. 3(a) provides a zoom-in view of the spectral component at 4.09 GHz, showing a 75-dB sidemode suppression ratio. The stability of the system is also evaluated. To do so, the system is allowed to operate in a room environment for a period of 10 min. The spectrum of the

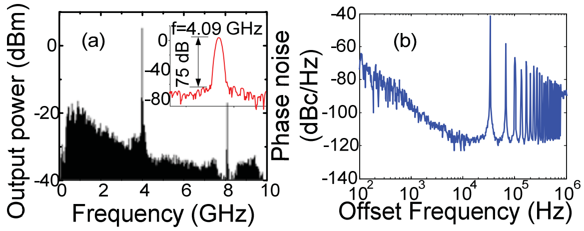

Fig. 3. (a) Electrical spectrum of the generated 4.09-GHz microwave signal. The frequency span is 10 GHz and the resolution bandwidth (RBW) is 1 MHz. Inset: zoomed-in view of the 4.09-GHz microwave signal. (b) Phase noise measurement of the generated 4.09-GHz microwave signal.

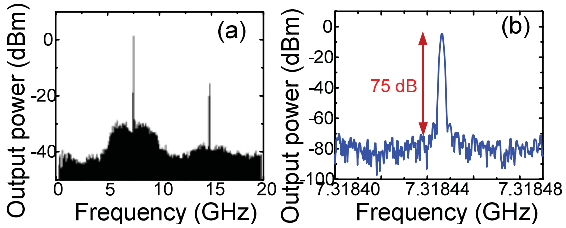

Fig. 4. (a) Electrical spectrum of the generated 7.318-GHz microwave signal. The frequency span is 20 GHz and the resolution bandwidth (RBW) is 1.5 MHz. (b) Zoomed-in view of the 7.318-GHz microwave signal.

4.09 GHz signal is stably shown on the ESA with negligible power variations.

The phase noise performance of the generated microwave signals is also studied. Fig. 3(b) shows the single-sideband phase noise spectrum of the generated 4.09 GHz microwave signal, measured by an Agilent E5052B signal source analyzer incorporating an Agilent E5053A downconverter. The phase noise of the generated microwave signal at an offset frequency of 10 KHz is lower than -120 dBc/Hz. Several peaks are observed for the offset frequency greater than 30 KHz. The spacing is identical to the FSR of the OEO resulted from the non-oscillating sidemodes. The first peak is located at 30 KHz offset frequency, which indicates that the length of the OEO loop is 6.897 km. The use of an LCFBG in the OEO loop could effectively reduce the length of the loop and then suppress the sidemodes.

The frequency tunability of the proposed OEO is then investigated, which is done by using a DCF with a smaller dispersion value of 339 ps/nm. The measured oscillation frequency is increased to 7.318 GHz, which again agrees well with the theoretical value of 7.4 GHz. Fig. 4(a) shows the spectrum of the generated 7.318 GHz microwave signal. Fig. 4(b) provides a zoom-in view of the spectral component at 7.318 GHz, showing again a 75-dB sidemode suppression ratio. The tunability is also investigated by tuning the channel spacing of the programmable optical filter. In the experiment, the channel spacing is reduced from 0.4 nm to 0.3 nm, as shown in Fig. 5(a). The oscillation frequency is then increased to 9.698 GHz. The theoretical result of the oscillation frequency is 9.8 GHz, an excellent agreement is again achieved. Fig. 5(b) shows the spectrum of the generated 9.698 GHz signal. The inset in Fig. 5(b) provides a zoom-in view of the spectral component at 9.698 GHz, showing a 50-dB sidemode suppression ratio.

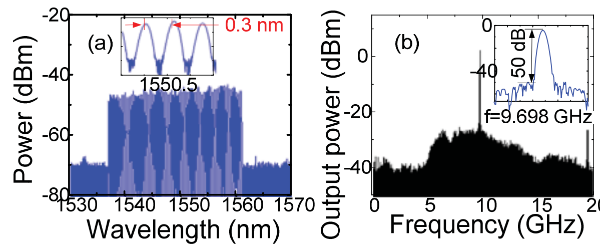

Fig. 5. (a) Measured optical spectrum of spectrum-sliced broadband source. Inset: zoomed-in view of the sliced spectrum. (b) Electrical spectrum of the generated 9.698-GHz microwave signal. The frequency span is 20 GHz and the resolution bandwidth (RBW) is 1.5 MHz. Inset: zoomed-in view of the 9.698-GHz signal.

IV. Conclusion

A tunable OEO implemented by employing a high-Q photonic microwave transversal filter without using any electronic microwave filters was proposed and experimentally demonstrated. The oscillation frequency can be tuned by tuning the channel spacing of the programmable optical filter or the chromatic dispersion of the dispersive element. An experiment was performed. The generation of frequency-tunable microwave signal with a tunable range as large as 9.7 GHz was demonstrated. A good phase noise performance with a phase noise of -120 dBc/Hz at an offset of 10 kHz was demonstrated.

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