Detection of laser carrier-envelope offset via photonic supercontinuum generation in silicon nitride waveguides

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***Abstract*—We implement detection of the carrier envelope offset (CEO) frequency of an erbium-fiber-based mode-locked laser, in the *f-3f* scheme via photonic supercontinuum generation in chip-scale silicon nitride waveguides. The achieved optical signal-to-noise ratio is ~30dB.**

Keywords—supercontinuum generation, self-referencing, carrier envelope offset, silicon nitride waveguides

I. Introduction

The development of high-brightness, highly coherent, and high-bandwidth laser sources, i.e. optical frequency combs, has opened the access to precise time and frequency measurement by optical meanings, and have enabled applications including laser spectroscopy, Lidar, and optical clocks[1]. Conventionally, optical frequency combs are fully stabilized by locking their two dimensional freedoms, i.e. the repetition frequency (f_{rep}) and carrier envelope offset frequency (f_{ceo}). The latter is by means of the so called self-referencing scheme that relies on the coherent spectral broadening of the laser to cover amount of octaves, and cooperates with high harmonic generation processes. In this way, a decent spectral overlap between the laser and its harmonics would enable the detection of the f_{ceo}. Since the first demonstration that was by an *f*-2*f* process, several variants have been developed as well, such as the 2*f*-3*f*[2], *f*-3*f*[3], and 3*f*-4*f*[4] self-referencing. Yet, for most of the cases, the spectral broadening and the harmonic generation are two separate and independent processes, leaving a complex and bulky system detrimental to the access of compact or miniatured optical frequency combs. In principle, supercontinuum generation is usually the technique for coherent spectral broadening[5], while second or higher order harmonic generations are based on nonlinear crystals that are non-centrosymmetric (i.e. supporting second and even-order nonlinearities).

Recently, there is an increasing interest on photonic supercontinuum generation based on chip integrated nonlinear waveguides[6]. Such waveguides, usually with a much larger refractive index contrast than silica fibers, could support sub-wavelength beam confinement and more efficient nonlinear processes. Therefore, supercontinuum with a spanning more than one octave (typ. two or three octaves) can be generated with a modest pumping energy. Another decisive factor is dispersion engineering that by CMOS compatible fabrication is lithographically controlled and precisely tuned. This has opened new approaches to self-referencing, particularly the much extended supercontinuum and the more efficient harmonic generation can be simultaneous implemented in the waveguide, finding spectral overlap, and enabling a direct detection of the f_{ceo}. Successful demonstrations include the *f*-3*f* self-referencing in silicon nitride waveguides with purely third order nonlinearity[7], and the *f*-2*f* scheme in lithium niobate on insulate waveguides with mixed second and third order nonlinearities[8]. Yet, challenges remain in the simultaneous control of both spatial (modal) overlap and temporal synchronization between the supercontinuum and the harmonics, in additional to the spectral overlap optimized by dispersion engineering.

Here, we demonstrate the detection of the laser carrier envelope offset of an erbium fiber based mode-locked laser by supercontinuum generation in chip scale silicon nitride waveguides, in the *f*-3*f* scheme. In particular, careful control both on the transverse modes of the third harmonic and on the pumping power dependent temporal synchronization was presented leading to optical signal-to-noise ratio(SNR) close to 30dB underlying the f_{ceo}.

II. Experimental Device

The experimental setup is shown in Fig.1(a), the pulse train is sent from an amplified 1560-nm mode-locked all-polarization-maintaining fiber laser with a pulse duration of 60 fs and a 106.9-MHz repetition rate. The fundamental TM mode of the waveguide is excited, which allows us to obtain the best third harmonic position. The output pulse is polarization-controlled in free space by a polarizer and a half-wave plate to achieve optimal coupling efficiency in the vertical polarization state (TM:17%),then, coupling to the silicon nitride waveguide, by adjusting the pump pulse power, the higher harmonics first appear, and as the pump power changes, the process obtains a supercontinuum broadening in the frequency domain while making the third harmonic and visible dispersive waves overlap as highly as possible. The light coupled out of the waveguide is then filtered in space through a bandpass filter to filter the visible light portion, which is collimated, attenuated and then incident into the photodetector.

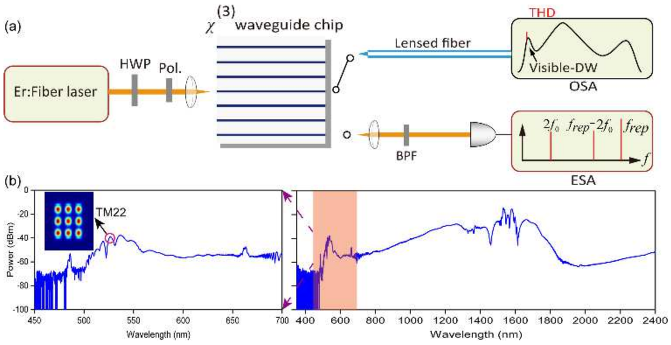

Fig.1 (a) Experimental setup of SCG and offset frequency extraction. HWP: half-wave plate; BPF: bandpass filter; Pol: polarizer; PD: photodetector; yellow line: free space; blue line: optical fiber path.(b) Left: Visible spectrum of dispersion wave overlapping with harmonic. Inset: High-order mode diagram corresponding to the third harmonic. Right: Complete SC spectrum of 1450nm wide waveguide.

However, it should be noted that the SNR of the RF signal obtained at this time is not necessarily optimal, and it needs to adjust the pump pulse incident power again and change the degree of time-domain pulse walk-off to obtain the best SNR of the offset frequency signal ($2f_{ceo}$) in the radio frequency spectrum.

III. Results

A 5 mm long waveguide structure with 1450*900 nm is used in our experiments, and the supercontinuum spectrum obtained when the pump pulse reaches the optimal pulse compression point is shown in Fig 1(b)(right), and the spectrum spans more than two octaves (400-2000nm) to meet the required spectrum range of f-3f.The highlight indicates the part focused by the offset frequency extraction(See the left figure for details),which shows a better spectrum overlap is achieved in the frequency domain. The illustration shows the high-order mode corresponding to the third harmonic.

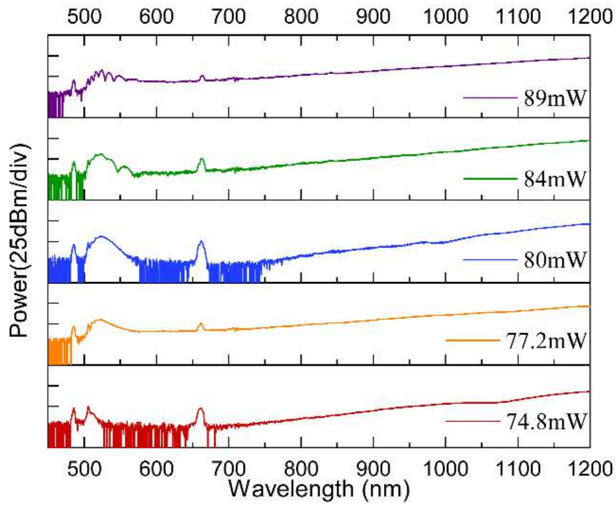

Fig.2 Measured spectra for various pump powers.

Fig.2 shows the evolution of the overlapping position and energy distribution of visible light dispersion wave and harmonic wave in the spectrum with the regulation of pump power when raising the SNR of offset frequency. This reflects the influence of pump power adjustment on time-domain pulse walk-off. The SNR of RF signals is improved in this process. When the pump power is 74.8mW, weak signals appear in the RF spectrum, and the SNR is only 5dBm. With the continuous improvement of power, the SNR oscillates first and then gradually increases. The best SNR shows that the time-domain pulse walk-off is minimum when the power is 89mW, see TABLE I. The decrease of the SNR when the pump power is 80mW may be attributed to the weak performance of the spectral intensity.

TABLE I. Evolution of the SNR of RF Signals

pump power (mW)	SNR (dBm)	pump power (mW)	SNR (dBm)
74.8mW	5	84mW	23
77.2mW	15	89mW	~30
80mW	10		

Meanwhile, according to the phase matching conditions of the third harmonic generation,

$$\Delta\beta = \beta(3\omega) - 3\beta(\omega) = (3\omega / c)\left[\bar{n}(3\omega) - \bar{n}(\omega)\right] = 0 \qquad (1)$$

The fundamental mode corresponding to the supercontinuum generation and the higher order mode corresponding to the third harmonic generation under this structure are simulated and analyzed, the corresponding distribution of near-field and far-field mode as shown in 3(a).The harmonic signal at 515 nm in the spectrum is consistent with the wavelength obtained by the phase matching condition, while the overlap between the centers of the fundamental and higher modes is found in the far-field distribution, which is again verified from the perspective of spatial mode overlap. However, the weak mode field of high-order modes in the overlapping range also limits the improvement of signal-to-noise ratio of offset frequency.

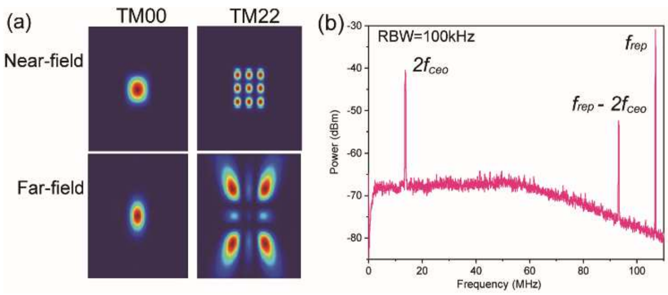

Fig.3 (a) Near and far-field simulation mode diagram of the fundamental mode and the higher-order mode generating the third harmonic. (b) The beat signal obtained directly from the waveguide output, with a SNR of ~30 dBm at 100 kHz RBW.

Through the analysis of the frequency domain, the pump power dependent time-domain pulse walk-off and spatial mode overlap to make it in the RF spectrum to show the RBW of 100kHz signal-to-noise ratio of ~30dBm offset frequency signal, as shown in Fig 3(b), and the pump pulse energy is 830pJ.

IV. Conclusions

In conclusion, we have achieved the extraction of carrier envelope offset frequency of a mode-locked fiber laser with a SNR of ~30 dBm by f-3f with 830pJ pump pulse energy in a silicon nitride photonic integrated waveguide without special structural design, which contributes to the transformation of mode-locked fiber lasers to compact and stable comb laser sources.

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