Integrated self-referenced frequency-comb laser based on a combination of fiber and waveguide technology

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Abstract: An optically integrated self-referenced frequency comb laser is demonstrated. The system consists of a passively-modelocked Er-fiber laser, a butt-coupled periodically poled lithium niobate (PPLN) waveguide phase-sensor and an electronic feedback loop for carrier-envelope-offset (CEO) phase stabilization. The f_{ceo}-beat-signal has a linewidth of 62 kHz and is detected with a S/N-ratio of 40 dB, with greatly reduced pulse energy requirements compared to bulk crystal phase-sensors**.** To our knowledge this is the first self-referenced frequency-comb system entirely based on guided-wave technology.

OCIS codes: (320.7090) Ultrafast lasers; (140.3510) Lasers, Fiber; (190.4370) Nonlinear Optics, Fibers; (130.3730) Integrated optics : Lithium niobate; (120.3930) Metrological Instrumentation

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1. Introduction

With the introduction of self-referenced frequency combs the complexity of the experimental setup required for precision optical frequency metrology was greatly reduced. Bulky frequency chains filling entire labs could be replaced by frequency combs based on table-top femtosecond lasers which are used as a clock-work to link optical frequencies to the RF regime and enable the link from optical frequencies at several hundred THz to the current definition of the time unit at ~9.2-GHz [1, 2]. Self-referenced frequency combs based on Ti:sapphire-laser technology are currently operated in many standard laboratories allowing precision optical frequency metrology at an unprecedented level of accuracy [3]. When locked to an optical frequency reference, self-referenced frequency combs currently provide the best available microwave oscillators for averaging times ranging from seconds to hours [4]. Besides the application of atom- or ion-referenced all-optical clocks, frequency comb based ultra-low-phase-noise RF oscillators are needed for novel developments in several technological areas including navigation, radar, remote sensing, high speed electronics, clock distribution, and communications. Frequency-comb systems used in those applications need to be compact and stable enough for portable instrumentation. Here, the lack of optical integration, need for realignment and high power consumption of present comb systems based on Ti:sapphire lasers are unsolved problems. As air- and space-borne applications for frequency metrology are currently being proposed [5, 6], the need for completely integrated, low noise, self-referenced frequency comb lasers operating unattended over long periods of time with low power consumption is evident.

Currently fiber laser alternatives [7-10] to Ti:sapphire based combs are developed, a technology enabling rugged design and long term operation. Despite not fully understood excess noise [11] the performance of those systems can be similar to Ti:sapphire-based combs [12, 13]. However, current fiber-frequency-comb lasers typically require relatively large pulse energies and pump powers due to inefficient carrier-envelope-offset (CEO) phase sensing. In such systems phase sensing is typically performed with f-2f interferometers involving frequency-doubling of the low frequency end of an octave-spanning continuum, though other schemes, not requiring an octave-spanning source at the expense of needed additional non-linear conversions are also possible [14]. For long term CEO-locked operation without phase slips the laser noise has to be sufficiently low. Typically a f-2f beat-note detection with more than 30-dB SNR in a 100-kHz resolution bandwidth is required. The power consumption of present laser systems is generally governed by the requirement of sufficient pulse energy in the continuum to enable frequency doubling of its low frequency wing. Even with bulk

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periodically poled $LiNbO_3$ (PPLN) frequency doublers[8] with second-harmonic conversion efficiencies of 100%/nJ, octave-spanning continua with an energy content of more than 1 nJ are generally required.

We show here that the power requirements for phase-sensing can be significantly reduced by implementing reverse-proton-exchanged (RPE) PPLN waveguides [15] as common-path *f*-2*f* interferometers. By comparing the mode-field diameter for bulk and waveguide PPLN one can estimate for the waveguide a theoretical SH conversion efficiency more than two orders of magnitude larger than for bulk PPLN. As a result, in an 86-MHz Er-fiber system we were able to reduce the required pulse energy for CEO-beat-frequency (f_{ceo}) detection by more than 50% while improving the S/N ratio by 10 dB. Note that the spectral intensity level at which the octave spanning requirement is fulfilled is significantly lower at 50% reduced pulse energy due to the highly nonlinear processes involved in continuum generation. This is the first optically integrated, self referenced frequency-comb laser based entirely on waveguide technology.

2. Experimental setup

The experimental setup of an optically integrated frequency-comb fiber laser is shown in Fig. 1. For the tests of the waveguide phase sensor a dispersion-compensated Fabry-Perot-type Er-oscillator modelocked with a saturable absorber was implemented. The design details including the chirped fiber grating employed for dispersion compensation were published elsewhere[8 , 16]. Here, an additional isolator after the amplifier was used to prevent feedback from the PPLN facet entering the amplifier. Both oscillator and amplifier were pumped by single-mode 980-nm pump diodes. The octave-spanning supercontinuum was generated by fusion splicing a short length of small-effective area germanium doped highly nonlinear fiber (HNLF) [17] to the amplifier. The HNLF dispersion slope was 0.024 ps/(nm^2 km) at 1550 nm. The supercontinuum was coupled into a RPE PPLN waveguide frequency doubler with a poling period of 26.45-μm designed to double a fundamental wavelength of 2128-nm at an operating temperature of 128°C.

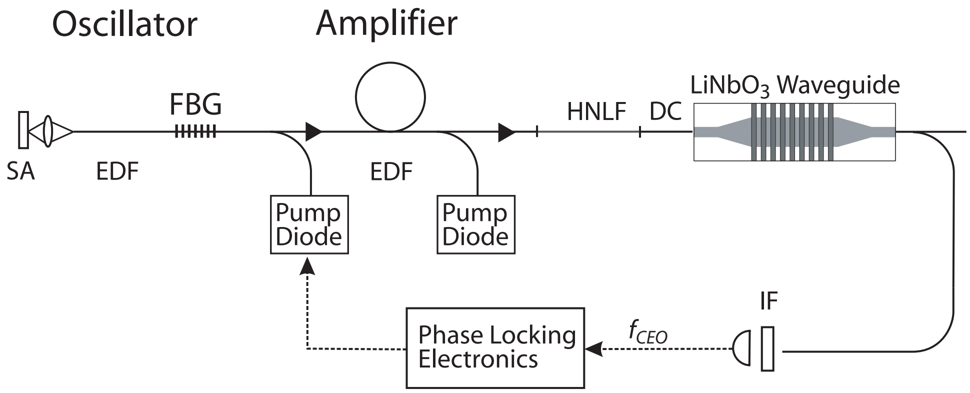

Fig. 1. Setup of an all guided wave frequency comb laser. SA: saturable absorber; EDF: Erbium doped fiber; FBG fiber Bragg grating; HNLF: highly nonlinear fiber; DC: dispersion compensation fiber; IF: interference filter.

The design of the RPE PPLN waveguide is illustrated in Fig. 2(a). The $LiNbO_3$ waveguide is 30-mm long and contains a 22.5-mm-long uniform periodically poled frequency-doubling section. The $LiNbO_3$ waveguide contains single-mode sections at the input and output ends for mode filtering and to simplify coupling. The theoretical mode profiles in the input and doubling section are shown in Fig. 2(a) above the waveguide. The frequency-doubling section is designed to maximize the mixing efficiency of the waveguide and to minimize any effects of waveguide non-uniformities on the doubling bandwidth. The excellent uniformity of the

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PPLN waveguide is further illustrated in Fig. 2(b), which is a measurement of the spectrum of the frequency-doubled light in the 1.06 μm region when pumped by the supercontinuum. The high frequency part of the continuum was blocked by a long-pass filter for this measurement. The 1.23-nm bandwidth is within 10% of the expected bandwidth of a perfectly uniform frequency doubling grating of 22.5-mm length.

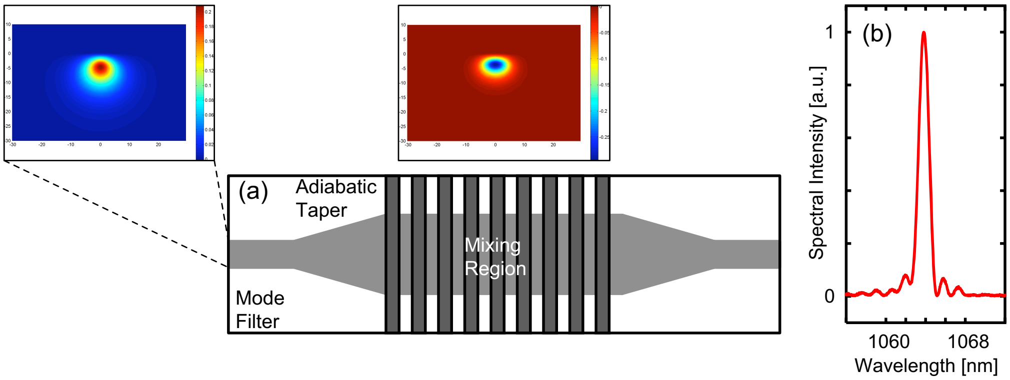

Fig. 2. (a) Schematic of the $LiNbO_3$ waveguide containing mode filters and adiabatic tapers at input and output end to match the mode size to a single-mode fiber. The mode-field diameter in the central mixing region is reduced to enhance harmonic conversion. (b) detected second-harmonic signal at the output, back coupled to a single-mode fiber. For this measurement the fundamental 1064 light in the supercontinuum was blocked in front of the waveguide by a long-pass filter and the waveguide was lens coupled.

Since the PPLN waveguide accepts both light in the 1 and 2-μm wavelength regions, it constitutes a common-path f-$2f$ interferometer. To compensate for the group-velocity walk-off between the fundamental and the second harmonic (SH) in the waveguide, an additional dispersion-compensation (DC) fiber is included between the waveguide and the highly nonlinear fiber (HNLF). Fig. 3 shows the calculated dispersion for waveguide and DC fiber. The difference of the waveguide group indices at 1.064-um and 2128-nm is of opposite sign and about 6 times larger in magnitude than the corresponding value for the DC fiber. Experimentally we found that we obtained the best SNR of the CEO related beat signal with approximately 8cm length of DC fiber, in good agreement with the calculated optimal group delay compensation for a SH photon generated at the center of the 30mm long waveguide. The waveguide dimensions at the waveguide input were designed to match the mode diameter of the DC fiber at a wavelength of 2128-nm. This choice allowed chromatic-aberration-free, low-loss butt-coupling of the DC fiber to the waveguide, launching an octave-wide spectrum into the waveguide. Index matching fluid was used to reduce the Fresnel reflections at the uncoated waveguide surface and a typical coupling efficiency of 66% was achieved. The coupling efficiency was determined by measuring the transmitted power and assuming 14% Fresnel reflection loss at the uncoated output surface and 0.2 dB/cm waveguide propagation loss. The output from the waveguide is coupled onto an InGaAs detector for detection and locking of the laser repetition rate f_{rep} and the carrier-envelope offset-frequency f_{ceo}.

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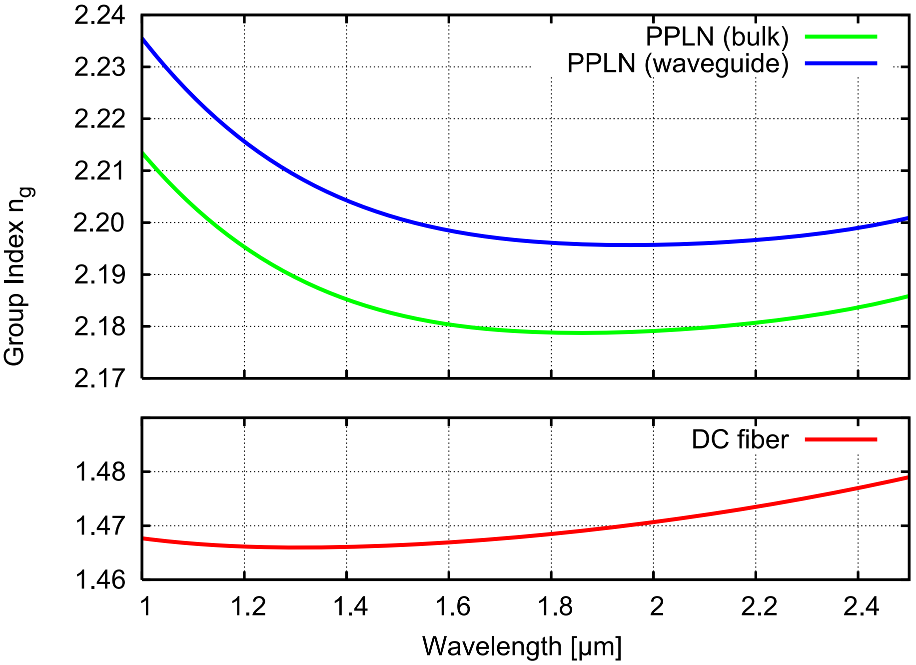

Fig 3. Calculated group index of the RPE-PPLN waveguide (top) and the dispersion compensating fiber (DC fiber, bottom). For comparison the group index of a bulk PPLN crystal is shown as well.

3. Experimental results

The RF spectrum of the laser measured with an InGaAs detector when using a bulk PPLN crystal as well as a RPE-PPLN-waveguide phase sensor is shown in Fig. 4. Using the waveguide sensor the amplifier pulse-energy could be reduced by more than 50% from 1.4-nJ to 0.6-nJ with a simultaneously improved SNR of 10-dB for the f_{ceo} beat signal compared with the bulk crystal. The amplifier pulse energy was obtained by measuring the average power after the DC fiber and dividing by the pulse repetition rate. The amplifier pulse energy could be coupled with minimal loss into the AR coated bulk PPLN crystal and with about 1.8-dB coupling loss into the RPE-PPLN-waveguide. Unfortunately, it is not possible to compare the obtained results using the bulk crystal and waveguide at the same pulse energy levels: At 0.6-nJ pulse energy no beat signal is detectable when using the bulk PPLN crystal. On the other hand at 1.4-nJ pulse energy the waveguide-based frequency doubler is overdriven and shows strong back-conversion effects. This leads to a significantly broader spectrum of the frequency doubled light compared to Fig 2(b) and a reduced conversion efficiency in the central part of the doubling bandwidth. In the experiment using the bulk PPLN crystal the DC fiber length was re-optimized, all other fiber lengths were kept unchanged.

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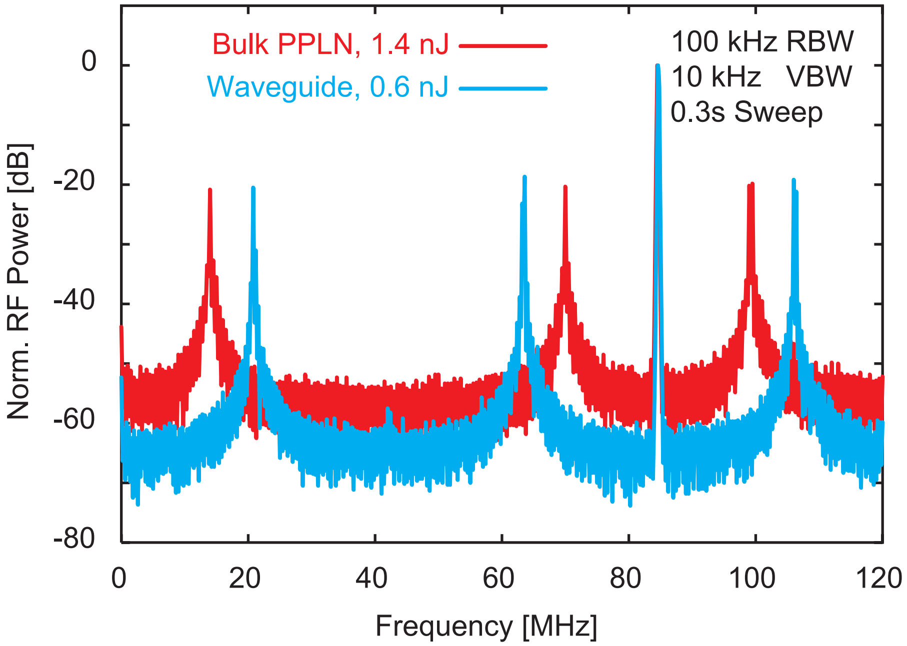

Fig. 4. Detected RF beat signals for comparison of bulk PPLN and waveguide sensor for 1.4 nJ and 0.6 nJ pulse energy respectively. The highest peak is caused by the intermode beat of the frequency comb and corresponds to the comb spacing or equivalently to the oscillator repetition frequency. The other peaks are caused by the CEO phase slip detected in a f-2f interferometer setup.

Figure 5(a) shows a zoom-in to the CEO-phase-slip related beat signal of the free running oscillator. We could fit the beat signal with a 62-kHz-FWHM Lorentzian line shape with good agreement with the data down to about -30dB from the peak. This is to our knowledge the narrowest f_{ceo}-beat-signal observed in a fiber-laser-based system reported so far. This result was mainly achieved by carefully dispersion compensating the oscillator cavity to a intracavity dispersion value close to zero. This was achieved by carefully designing the fiber Bragg grating to cancel the dispersion of the intracavity fiber and fabricating the grating with less than 40fs rms group delay ripple.

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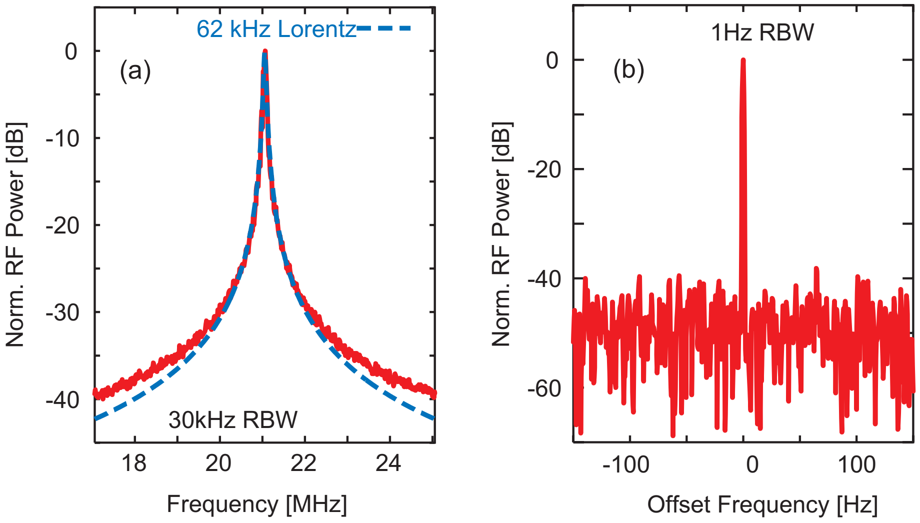

Fig. 5. (a): Detected RF beat signal of the free running oscillator. The bandwidth of the free running f_{ceo} related beat signal could be fitted with a 62-kHz FWHM Lorentzian line shape (b) f_{ceo}-related beat signal of the CEO-locked oscillator.

We phase locked the beat signal to an external RF oscillator by controlling the pump-diode current using a phase-locked-loop circuit with a digital phase detector without any problems over hours. The free running beat-note S/N ratio of 40 dB should allow phase locking for months on end without phase-slips. The RF beat signal of the CEO locked oscillator is shown in Fig 5(b). A narrow spectral feature whose linewidth is limited by the spectrum-analyzer resolution bandwidth of 1 Hz is detected with 40dB SNR, indicating a stable lock.

In view of the extreme non-linear spectral broadening process in HNLF fibers the observed reduction in pulse energy is quite significant. Currently the power level of the doubled 2128-nm light exceeds the fundamental 1064-nm light significantly. The minimum launched power for sufficient S/N ratio on the beat signal is now determined by the spectral intensity requirements at the high frequency part of the comb. The generation of continua with enhanced high frequency spectral components have been demonstrated using UV-irradiated highly nonlinear fibers [18]. Using these fibers for spectral broadening, the required amplifier power can be significantly reduced. Further reduction of the required power is expected by the use of highly nonlinear fibers based on multi-component glasses, which can generate octave-spanning spectra for pulse energies as low as 0.1nJ[19].

4. Conclusion

In conclusion we have demonstrated the first optically integrated self-referenced frequency-comb-laser system based entirely on guided-wave technology. The system is based on an ultra-compact Er-fiber-laser-based comb generator integrally coupled to a RPE-PPLN-waveguide phase sensor. Due to the low pulse energy requirements with the RPE-PPLN-waveguide phase sensor we are convinced that this technology can be upgraded to high-repetition-rate systems. We believe with this technology it is possible to deliver fiber-based self-referenced frequency-comb lasers operating at gigahertz repetition rates with low power requirements and unprecedented long-term stability.

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