Ultralow phase noise microwave generation with an Er:fiber-based optical frequency divider

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We present an optical frequency divider based on a 200 MHz repetition rate Er:fiber mode-locked laser that, when locked to a stable optical frequency reference, generates microwave signals with absolute phase noise that is equal to or better than cryogenic microwave oscillators. At 1 Hz offset from a 10 GHz carrier, the phase noise is below −100 dBc/Hz, limited by the optical reference. For offset frequencies >10 kHz, the phase noise is shot noise limited at −145 dBc/Hz. An analysis of the contribution of the residual noise from the Er:fiber optical frequency divider is also presented.

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Generating and distributing microwave signals with low phase noise is compelling for scientific applications such as remote synchronization at large facilities [1], local oscillators for fountain clocks [2], and very long baseline interferometry [3]. Fabry–Perot optical cavities can have quality factors approaching 10^{11} and can serve as ultrastable optical frequency references when a CW laser is locked to a cavity resonance [4]. Combining this optical frequency reference with the high-fidelity frequency division of an optical frequency comb allows for the realization of microwave signals with phase noise surpassing state-of-the-art microwave oscillators [5,6]. This was recently demonstrated with a Ti:sapphire-based optical frequency divider (OFD) locked to an ultrastable optical frequency reference, where phase noise of −104 dBc/Hz at 1 Hz offset from a 10 GHz carrier was reported [7]. Achieving this same level of performance in Er:fiber-based OFDs would also be of interest, since the 1550 nm center wavelength of Er:fiber is advantageous for large-scale pulse distribution and the lower cost and power requirements make fiber lasers more amenable to a compact, mobile microwave source. Recent measurements of Er:fiber-based OFDs have shown the potential of these lasers to generate microwaves with extremely low phase noise close to carrier. Residual noise of −120 dBc/Hz at 1 Hz offset from a 11.55 GHz carrier was shown, and noise at larger offset frequencies was limited to −130 dBc/Hz [8]. However, phase noise comparisons between an independent Er:fiber-based and Ti:sapphire-based system have been significantly higher, limited to −90 dBc/Hz at 1 Hz offset and −120 dBc/Hz at larger offset frequencies on a 9.2 GHz carrier [5]. Here we report on an Er:fiber-based OFD capable of producing 10 GHz microwaves with absolute phase noise below −100 dBc/Hz at 1 Hz offset, limited by the optical frequency reference. For offset frequencies >10 kHz, the phase noise is shot noise limited at −145 dBc/Hz. As discussed in detail below, key to our demonstration of low phase noise is a 200 MHz repetition rate laser, with a high-speed intracavity modulator, and low intrinsic relative intensity noise (RIN). The demonstrated phase noise meets or exceeds the 10 GHz phase noise from cryogenic microwave oscillators [9] and is more than 40 dB lower than 10 GHz room temperature oscillators at 1 Hz offset frequency [10].

The frequency division process may be described as follows. When one mode of an optical frequency comb is phase locked to an optical reference, the pulse repetition rate f_{rep} may then be expressed as $f_{\mathrm{rep}} = (\nu_{\mathrm{opt}} - f_0 - f_b)/n$, where ν_{opt} is the frequency of the optical reference, f_0 is the comb offset frequency, f_b is the difference frequency between the optical reference and a comb mode, and n is an integer of the order of 10^5–10^6. Thus, f_{rep} represents the frequency-divided optical reference. Accessing f_{rep} is achieved by photodetecting the optical pulse train to generate a series of discrete tones at harmonics of f_{rep}. Any harmonic of f_{rep} within the photodetector (PD) bandwidth may be selected as a microwave source.

The advantage of this technique is derived from the fact that frequency division from optical to microwave is accompanied by a large reduction in the phase noise power spectrum, given by $L(f)_{\mathrm{microwave}} = L(f)_{\mathrm{optical}}/N^2$. Here L is the single-sideband phase noise, and N is the optical-to-microwave frequency ratio. Thus, for an optical frequency reference at 282 THz, the phase noise is reduced by ~90 dB when converted to a 10 GHz microwave signal. Assuming perfect fidelity frequency division, optical phase noise below $-10f^{-3}$ dBc/Hz of a state-of-the-art 282 THz optical frequency reference leads to phase noise below $-100f^{-3}$ dBc/Hz on the derived 10 GHz carrier.

A schematic of the Er:fiber mode-locked laser, f_0 detection, and f_b generation is shown in Fig. 1. A 40 cm length of highly doped Er gain fiber is pumped by two polarization-multiplexed 980 nm diodes. A short free-space section includes wave plates and a polarization beam splitter (PBS) to excite nonlinear polarization rotation mode locking. The free-space section also includes a 4 cm long $\mathrm{LiNbO_3}$ phase modulator for cavity length stabilization [11]. The control bandwidth of the cavity length with the $\mathrm{LiNbO_3}$ crystal is ~300 kHz, sufficient to suppress most seismic and acoustic disturbances to the mode-locked laser cavity. Considering the length of

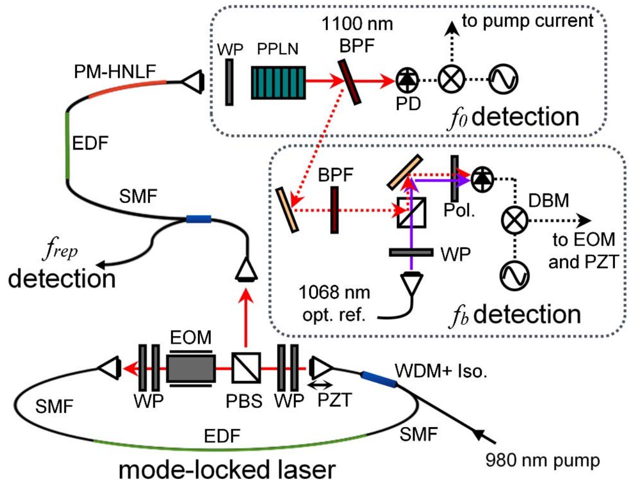

Fig. 1. (Color online) Er:fiber-based OFD. EDF, erbium-doped fiber; PPLN, periodically-poled LiNbO$_3$; Pol., polarizer; DBM, double-balanced mixer; opt. ref., optical reference; WDM+ Iso., wavelength division multiplexer/isolator hybrid; PZT, piezoelectric transducer; WP, wave plate; other symbols are defined in the text.

the Er-doped fiber, 44 cm of single-mode fiber (SMF), and the LiNbO$_3$ crystal, the estimated cavity dispersion is $2 \cdot 10^{-3}\,\mathrm{ps}^2$ at 1550 nm. The laser output is taken at the rejection port of the PBS, resulting in ~70 mW average power for pump power ~1 W. The optical spectrum spans 100 nm at points 10 dB down from the maximum.

The laser output is split, with half the output used for f_{rep} detection and monitoring, while the rest is first amplified to ~300 mW with an Er-doped fiber amplifier, then sent through 70 cm of polarization-maintaining, highly nonlinear fiber (PM-HNLF). The pulse width into the PM-HNLF is below 100 fs. After the PM-HNLF, the optical spectrum spans more than one octave, from 1050 to 2250 nm, suitable for f_0 detection in an $f - 2f$ interferometer. Frequency doubling of the 2200 nm light is accomplished in periodically poled LiNbO$_3$. A 10 nm wide bandpass filter (BPF) centered at 1100 nm rejects light that does not contribute to the f_0 beat. A short piece of SMF after the PM-HNLF ensures overlap between the pulses at 1100 and 2200 nm for high signal-to-noise on f_0, typically 45 dB at a measurement resolution bandwidth of 300 kHz. The error signal generated from the f_0 beat is applied to the pump current.

The wavelength of the optical frequency reference used in this Letter is 1068 nm (282 THz). The linewidth of this laser is below 1 Hz, with an Allan deviation $<8 \cdot 10^{-16}$ in 1 s. It is sent from a separate laboratory in the building to the Er:fiber comb via 300 m of noise-canceled optical fiber [12]. While the wavelength of the optical frequency reference is not directly accessible with the Er:fiber comb, it can be combined with the comb light rejected from the BPF in the $f - 2f$ interferometer to generate a beat of sufficient signal-to-noise, >30 dB at 300 kHz resolution bandwidth. High bandwidth locking of this beat signal is accomplished via feedback to the intracavity electro-optic phase modulator (EOM), whereas low-bandwidth/large dynamic range locking of f_b is achieved via a piezoelectric transducer on one intracavity fiber launcher translation stage.

As the phase noise level of the generated microwaves is significantly lower than any commercially available source, the phase noise was measured by comparing against an independent Ti:sapphire OFD referenced to a stabilized 578 nm (518 THz) laser [4]. The repetition rates of the two systems are slightly offset to create a frequency difference of the 10 GHz harmonic of a few megahertz. The pulse trains were detected with p-i-n photodiodes designed for increased power handling [13], then filtered to select a harmonic near 10 GHz, amplified with low phase noise amplifiers, then combined in a double-balanced mixer. The beat signal at the output of the mixer is then compared to a quartz-based 10 MHz reference using digital phase comparison. The resulting phase noise comparison of the 10 GHz signals is shown at (a) in Fig. 2. At 1 Hz offset, the 10 GHz phase noise is below −100 dBc/Hz, limited by the phase noise of the optical references, shown at (b) in Fig. 2. Assuming both optical frequency references contribute equally, the phase noise of the Er:fiber-based OFD is ~ − 103 dBc/Hz at 1 Hz offset. The limit imposed by the optical references was determined by comparing the optical phase noise between the 1068 and 578 nm signals, using the Ti:sapphire optical frequency comb to span the 236 THz frequency gap [7]. The optical phase noise level was then scaled to a 10 GHz carrier, assuming perfect fidelity division, by subtracting 90 dB from the optical phase noise. A separate microwave phase noise measurement between this Ti:sapphire OFD locked to the 578 nm reference and another Ti:sapphire OFD locked to the 1068 nm reference revealed a phase noise level given at (c) in Fig. 2. More details on the phase noise from the Ti:sapphire systems may be found in [7]. Thus the contribution of the Ti:sapphire OFD to this measurement system is only due to the 578 nm frequency reference, and only close to carrier. Phase noise of the 10 MHz reference is also shown at (d) in Fig. 2 and is seen to limit the phase noise measurement for offset frequencies 4 Hz–10 Hz.

For offset frequencies greater than 10 Hz, several noise sources contribute to the measured 10 GHz phase noise level, including residual noise of the Er:fiber OFD; PD flicker noise [14], shot noise, and amplitude-to-phase noise conversion of the laser (RIN); and fiber noise from the OFD to the PD. Here we highlight the contributions

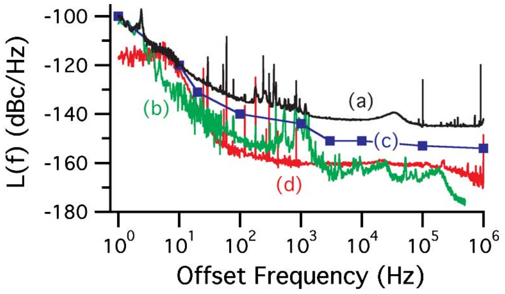

Fig. 2. (Color online) Single-sideband phase noise on a 10 GHz carrier. (a) Phase noise comparison between Er:fiber-based OFD and Ti:Sapphire-based OFD. (b) Optical phase noise comparison between the 1068 and 578 nm optical references, scaled to a 10 GHz carrier, assuming perfect fidelity division. (c) Phase noise contribution from the Ti:sapphire-based OFD. (d) Phase noise contribution of the measurement system's 10 MHz reference.

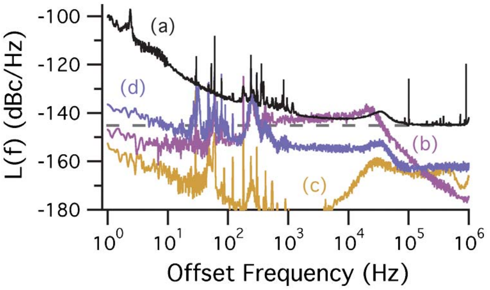

Fig. 3. (Color online) Phase noise limitation imposed by the Er:fiber-based OFD. (a) Microwave phase noise on 10 GHz carrier from (a) in Fig. 2. (b) Phase noise from f_0 lock. (c) Phase noise from f_b lock. (d) RIN converted to phase noise at the PD. The dotted horizontal line is the shot noise limit.

from noise sources directly related to the use of the Er:fiber-based OFD, namely shot noise, the residual noise of the Er:fiber OFD, and RIN. These noise contributions are shown in Fig. 3, along with the 10 GHz phase noise of (a) in Fig. 2. Curves (b) and (c) in Fig. 3 show the residual phase noise from f_0 and f_b, respectively, of the Er:fiber OFD. As with the optical comparison, 90 dB was subtracted from the measured data to scale to a 10 GHz carrier. Although the f_0 residual noise data were measured with slightly different lock conditions, it is nevertheless clear that this noise dominates the phase noise spectrum from ~1 to 50 kHz. The residual noise of f_b is significantly lower and does not contribute to the 10 GHz phase noise. A possible route to reduce the impact of the f_0 noise is to use the transfer oscillator technique of [15], effectively “mixing out” f_0. However, in our experience, independently locking f_0 can reduce the laser RIN.

The calculated shot noise level is shown as the horizontal dashed line in Fig. 3. This level was calculated using the time-invariant shot noise formula, with 4.36 mA of average photocurrent and power of the 10 GHz harmonic of −19.4 dBm. The power at 10 GHz was limited by saturation in the PD, which in turn bounded the achievable shot-noise-limited signal-to-noise to −145 dBc/Hz. The shot noise level relates to the use of the Er:fiber-based system in that the PD saturation level depends strongly on the repetition rate of the pulse train on the PD, with higher repetition rates leading to higher output saturation power [16]. To date, f_{rep} from Er:fiber-based optical frequency combs is limited to a few hundred megahertz, whereas f_{rep} of Ti:sapphire optical frequency combs has scaled as high as 10 GHz [17].

RIN can impact the 10 GHz phase noise through amplitude-to-phase conversion in photodetection [13]. The RIN of the Er:fiber laser was measured to be −125 dB/Hz at 1 Hz, decreasing to −145 dB/Hz at 1 kHz. Taking into account separate measurements on the amplitude-to-phase conversion coefficient using an Er:fiber mode-locked laser on a similar PD, as well as shape of the RIN power spectrum, an upper limit can be placed on the projection of the RIN onto the phase noise. This “worst case” projection is shown at (d) in Fig. 3. For the Er:fiber laser system shown here, the RIN minimally contributes to the 10 GHz phase noise. Possible sources of the phase noise level for offset frequencies 10 Hz to 1 kHz include PD flicker and noise originating in the fiber link between the OFD and PD. The contribution of these sources is currently under investigation.

In conclusion, a Er:fiber-based OFD has been used to generate a 10 GHz signal with ultralow absolute phase noise. At 1068 nm, the optical reference wavelength was well outside the mode-locked spectrum of the Er:fiber laser. Locking to the optical reference was achieved by using part of the octave required for f_0 detection. Using this technique, it should be possible to use virtually any optical frequency reference from 1 to 2 μm with an Er:fiber OFD for low-noise microwave generation.

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