Optical frequency division for ultralow phase noise microwave generation

F. N. Baynes\textsuperscript{5,1}, F. Quinlan\textsuperscript{1}, T. M. Fortier\textsuperscript{1}, A. Beling\textsuperscript{2}, Q. Zhou\textsuperscript{2}, A. Cross\textsuperscript{2}, J. C. Campbell\textsuperscript{2}, and S. A. Diddams\textsuperscript{1,1}

\textsuperscript{1}National Institute of Standards and Technology, Boulder, USA
\textsuperscript{2}Department of Electrical Engineering, University of Virginia, Charlottesville, VA
\textsuperscript{5}frederick.baynes@nist.gov, \textsuperscript{1}sdiddams@boulder.nist.gov

Abstract—A stable optical frequency is phase-coherently divided to generate ultralow-noise 10 GHz signals having phase noise below -100 dBc/Hz at 1 Hz and a white noise of -177 dBc/Hz at higher offset frequencies. We discuss the technical and fundamental challenges of this approach, along with potential for integration of the components in a portable and robust system.

Keywords—microwave photonics; phase noise; ultrafast optics; optical cavities.

I. INTRODUCTION

The coherent division of the optical frequency of a cavity stabilized laser provides microwaves with exceptional spectral purity [1]; signals at 10 GHz with absolute phase noise below -100 dBc/Hz at 1 Hz offset have been created with this technique. The applications of such spectrally pure signals include radar and sensing, high-speed signal processing, analog-to-digital conversion and time and frequency dissemination. Here we describe the technical and fundamental challenges to achieving the lowest phase noise floors and further discuss advances required to develop a portable and robust system amenable for use out of the laboratory.

The photonic generation of low noise microwaves by optical frequency division (OFD) consists of three main elements, shown in Fig. 1. First, a cavity-stabilized laser serves as an optical frequency reference with sub-Hertz linewidth [2]. The frequency of the cavity-stabilized laser is coherently divided with a self-referenced optical frequency comb. In the time domain, the frequency comb produces a train of ultrashort optical pulses whose repetition rate \( f_{\text{rep}} \) is given by the comb spacing. Photodetection then converts the optical pulse train to an electrical pulse train. In the frequency domain, the electrical signal is a series of discrete tones at harmonics of \( f_{\text{rep}} \), any one of which may be selected as a low noise microwave source. The phase noise power spectrum of a harmonic of \( f_{\text{rep}} \) is that of the cavity-stabilized laser divided by \( N^2 \), where \( N \) is the optical-to-microwave frequency ratio. For a 300 THz optical frequency divided down to 10 GHz, this results in a phase noise reduction of ~ 90 dB.

We have achieved the best phase noise results to date with laboratory optical frequency reference cavities designed for optical clock spectroscopy, Kerr-lens mode-locked Ti:sapphire frequency combs, and unpackaged, wafer-level high power photodetectors [3]. Moreover, the optical reference cavities have resided in a separate laboratory, linked to the frequency comb through noise-cancelled fiber. Developing a portable optical frequency divider (OFD) requires collocating compact and robust optical reference cavities, optical frequency combs and high power photodetectors while maintaining the low noise performance of laboratory systems. In this paper, we focus on our recent progress in the development of a compact frequency comb, and the characterization of a packaged, high performance photodetector.

Fig. 1. Overview of optical frequency division (OFD) for high-spectral-purity microwave generation. A continuous wave (CW) laser is locked to a high Q optical resonator, resulting in a sub-Hertz linewidth laser. A combine of an optical frequency comb is then locked to the stabilized laser, transferring its stability to all comb modes. In the time domain, the comb is a train of ultrashort optical pulses that are photodetected to generate a train of electrical pulses. Bandpass-filtering (BP) the electrical pulse train produces a low noise microwave at a chosen harmonic of the pulse repetition rate.

II. TOWARDS A PORTABLE OPTICAL FREQUENCY DIVIDER

Ti:sapphire optical frequency combs offer extremely low intrinsic noise, high output power and high repetition rate, all of which are advantageous to low noise microwave generation via optical frequency division. However, delicate alignment, environmental sensitivities, and a large-scale pump laser restrict their use to the laboratory. An alternative for long term, robust operation is the Er:fiber-based optical frequency comb. Both Er:fiber laser and Ti:sapphire laser-based OFDs have demonstrated low close-to-carrier phase noise, as shown in Fig. 2 [4]. For offset frequencies greater than 1 kHz, however, Ti:sapphire OFDs significantly outperform fiber-based OFDs.

A significant source of phase noise in Er:fiber based OFDs is the intrinsic noise of the Er:fiber laser. Locking the comb
spacing to the optical reference may be accomplished by detecting and independently controlling the carrier-envelope offset beat ($f_{\text{ceo}}$) and the beat between the optical reference and one tooth of the frequency comb ($f_0$). In this case, the fiber laser OFD noise that dominates the microwave phase is residual noise of $f_{\text{ceo}}$. An alternative locking method is to mix in the rf domain $f_{\text{ceo}}$ and $f_0$, and lock the resulting $f_{\text{ceo}} + f_0$ signal with a single actuator [5]. This keeps the comb spacing locked to the optical reference while $f_{\text{ceo}}$ and $f_0$ are allowed to vary. Using this technique, we have demonstrated residual phase noise with a 25 dB improvement in the Er:fiber intrinsic noise at 10 kHz offset, also shown in Fig. 2. At this noise level, Er:fiber OFD intrinsic noise becomes comparable to that of Ti:sapphire OFDs, but with the advantage of a smaller footprint and robust operation.

![Graph showing comparison of absolute noise levels](image)

**Fig. 2.** Comparison of the 10 GHz absolute phase noise from a Ti:sapphire based OFD and an earlier Er:fiber based OFD, and residual noise on $f_{\text{ceo}}$ of the Er:fiber OFD for two locking configurations. For the residual noise plots (grey and red traces), the noise has been scaled to a 10 GHz carrier for direct comparison to the OFD absolute noise. The absolute noise of the Ti:sapphire (Ti:S, blue curve) is the measured contribution of two independent devices. Accounting for this and the noise contribution of electronic amplifiers, we arrive at a noise floor of -177 dBc/Hz for a single OFD-based oscillator.

For large offset frequencies, shot and thermal noise become the dominant phase noise sources. In Fig. 2, this is the case for the Er:fiber OFD phase noise for offset frequencies beyond ~100 kHz, and for the Ti:sapphire OFD beyond ~2 MHz. With sufficiently short optical pulses illuminating the detector, the shot noise contribution to the phase noise becomes negligible. This is due to correlations in the shot noise spectrum that shift the noise from the phase to the amplitude quadrature [6]. In this case, the phase noise limit at high frequencies is ideally thermal noise, and can be reduced by increasing the microwave power. High saturation power is therefore critical for the lowest noise performance. In the detection of high power ultrashort optical pulses, space charge effects can reduce the achievable microwave power. For Er:fiber-based OFDs, this effect is exacerbated by the fact that the pulse repetition rate is often 10-100x lower than the desired microwave signal frequency. For improved power handling capability, we use a modified uni-travelling carrier (MUTC) photodetector, built for high saturation current and high linearity [7]. For our OFD results to date, microwave signal extraction was performed with a microwave probe mounted on an XYZ translation stage, and thermoelectric cooling was required to prevent catastrophic thermal failure at high photocurrent operation. For a portable system, MUTC detectors have now been integrated with the thermoelectric cooler in a fiber pigtailed package. Microwave power saturation at 10 GHz for the packaged MUTC is shown in Fig. 3. For this measurement, a fiber optic pulse interleaver was used to multiply the pulse repetition rate from an Er:fiber frequency comb [8]. This strongly mitigates the space charge effect and improves the microwave saturation power by more than 20 dB. The integrated thermoelectric cooler was used to hold the detector at room temperature. As shown in Fig. 3, microwave power >20 dBm at average photocurrents > 60 mA was demonstrated. This 10 GHz power level represents the highest demonstrated from a packaged photodetector under short pulse (<10 ps) illumination. Also, no degradation of the PDs electrical bandwidth was observed. Thus high performance was maintained in the transition from an on-wafer detector to a robust package.

![Graph showing 10 GHz absolute noise levels](image)

**Fig. 3.** The output power of the MUTC photo-detector at 10 GHz from the detection of pulse interleaved ultra-short pulses from an Er:fiber comb. Inset: photograph of a packaged MUTC photodetector with integrated thermoelectric cooler.

### III. Conclusion

Ultra-low phase noise microwaves generated through an optical frequency divider are among the most spectrally pure signals available today. For the technology to be available outside a laboratory environment, it is important to move to more robust and integrated systems. Improvements to the intrinsic noise of Er:fiber OFDs and the creation of packaged high power photodetectors indicate that the state-of-the-art performance of previous systems can be maintained in a more integrated and robust package.

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