Low-noise synthesis of microwave and millimetre-wave signals with optical frequency comb generator

S. Xiao, L. Hollberg and S.A. Diddams

The phase noise of a 20 GHz picosecond optical pulse train generated by a modulator-based optical frequency comb generator is analysed. The residual timing jitter is ≤10 fs for Fourier frequencies from 10 Hz to 10 MHz. Photodetection of the optical pulse train provides millimetre-wave signals with similarly low residual jitter at 40, 60, and 80 GHz with applicable powers of −7.5, −10.5, and −13 dBm, respectively.

Introduction: Photonic-based generation of microwave and millimetre-wave signals has been pursued by many groups over the years [1]. Common approaches involve modulating and/or mixing CW lasers to generate sidebands or beat frequencies over the range of approximately 30–300 GHz [2–5]. The optical beat frequencies are converted to high speed electrical signals via photodetection or photomixing. In this regard, an optical frequency comb generator (OFCG) based on a high-seed phase modulator inside a resonant Fabry-Pérot cavity [6,7] has some unique advantages. In a very simple package, it directly provides an array (separated by the modulation frequency) of precisely known optical frequencies spanning many terahertz in the 1.5 μm spectral region. In addition to the comb-like spectral structure, the time-domain output of the OFCG is a high-repetition-rate train of short pulses (≤1 ps) [8–12]. Photodetection of the pulse train provides repetitive current pulses which themselves correspond to a comb of microwave and millimetre-wave harmonics extending up to the bandwidth of the detector. Thus, one can use low-noise and low-loss photonic techniques to synthesise a broad array of millimetre-waves, extending through the K, V and W-bands (20–100 GHz), starting from the original X-band (10 GHz) sinusoidal driving frequency. The purpose of this Letter is to evaluate the OFCG's performance – both in terms of the achievable powers and residual phase noise – for low-noise frequency synthesis of microwave and millimetre-wave signals.

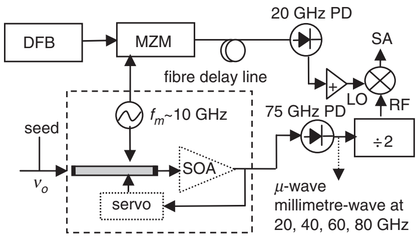

Fig. 1 *Schematic experimental setup for signal generation and noise measurement*

v_o: frequency of optical CW seed laser; PD: photodiode; SOA: semiconductor optical amplifier; SA: spectrum analyser; MZM: Mach-Zehnder amplitude modulator

Experiment and measurement: Fig. 1 shows the experimental setup with a waveguide OFCG. The lithium niobate waveguide Fabry-Pérot cavity is modulated at 10 GHz and simultaneously servo-locked to a narrow linewidth CW seed laser at 1550 nm. The temporal output is a 20 GHz pulse train composed of two interleaved 10 GHz pulse trains. Further details of the operation of the OFCG can be found in [6, 7, 12]. The output of the OFCG is amplified with a semiconductor optical amplifier (SOA), which consists of 20 GHz picosecond pulses with an optical power of +10 dBm [12]. 10% of the power (~0 dBm) split from the SOA output was used for the servo system, which was configured to minimise the microwave power detected at 10 GHz, and this enables high-fidelity generation of 20 GHz harmonics, e.g. 20, 40, 60, 80 GHz, over an indefinite time. Details of the servo can be found in [12]. All parts in the dashed box in Fig. 1 may be integrated into a compact, portable package. The average optical power was +9.5 dBm at the fast photodiode with a −3 dB electrical bandwidth of ~75 GHz (impulse response width ~8 ps), and the corresponding photocurrent was 5 mA. The resulting electrical pulses have a width of approximately 9 ps and a peak voltage of 0.55 V into 50 Ω. Fig. 2*a* shows the corresponding microwave spectrum measured with the combination of a spectrum analyser (DC–40 GHz) and a harmonic mixer (50–80 GHz). Powers of −4.5, −7.5, −10.5, and −13 dBm were measured at 20, 40, 60, and 80 GHz, respectively. The decreasing power of these harmonics is due to limited electrical bandwidth of the photodiode, which is operated near saturation. We account for the conversion loss of the harmonic mixer, but additional losses at the level of 1 to 3 dB may arise from the connectors. The spectrum of Fig. 2*a* also shows residual power at odd harmonics (10, 30, 50, 70 GHz), which is mainly due to imbalance (power and pulse profile) between the two interleaved 10 GHz pulse trains after the non-uniform optical amplification.

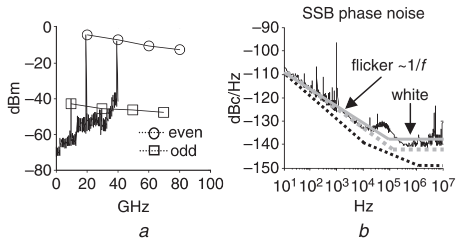

Fig. 2 *RF spectrum of 20 GHz output pulse, and measured residual SSB phase noise of 10 GHz signal at frequency divider output*

a RF spectrum of 20 GHz output pulse
Continuous spectrum (0–40 GHz) measured with spectrum analyser. Resolution bandwidth (RBW) 30 kHz. Noise floor is that of spectrum analyser. Four discrete data at 50, 60, 70, 80 GHz measured with harmonic mixer. Connected squares indicate measured power at odd harmonics (10, 30, 50, 70 GHz): connected circles indicate measured power at even harmonics (20, 40, 60, 80 GHz)
b Measured residual SSB phase noise of 10 GHz signal at frequency divider output
Black dotted, grey dotted and grey curves are sketches of SSB phase noises of frequency divider, mixer including microwave amplifier, and SOA, respectively

We characterise the excess phase noise of the 20 GHz harmonic as illustrated in Fig. 1, and the timing jitter is calculated by the integration of the phase noise. Measurement of the residual phase noise was achieved by first dividing the 20 GHz signal by two electronically and then mixing to DC with the original 10 GHz modulation. The resulting voltage fluctuations were recorded with an FFT spectrum analyser. To accurately measure the residual noise, we introduce an additional modulator and optical delay to balance the delay between the two arms of the microwave interferometer [13]. The conversion from microwave to optical (MZM), and conversion back to microwave was independently verified to have phase noise below that measured for the OFCG. Fig. 2*b* plots the experimental SSB phase noise $L(f)$ at 10 GHz in black. Additionally, Fig. 2*b* shows the approximate residual phase noise of the frequency divider (black dotted curve), the noise floor attributed to the mixer and the microwave amplifier (grey dotted curve), and the excess phase noise due to the semiconductor optical amplifier (grey curve, measured with a 10 GHz MZM modulation input).

The measured noise $L(f)$ mainly consists of $1/f$ flicker noise for Fourier frequencies ≤ 10 kHz and white noise starting at Fourier frequencies near 0.3 MHz. These two types of noise reach the measured noise floor from the semiconductor optical amplifier, which is the major limiting factor in our current setup. The excess noise between 1 and 10 MHz is attributed to residual intensity noise on the seed laser as well as the optical amplifier. The spike at 1 kHz arises from the dither signal applied for stabilisation [12]. Better attention to ground loops and shielding of the microwave interferometer may remove several of the bright lines corresponding to 60 Hz harmonics seen in the measurement traces. For the measured phase noise, the total integrated RMS residual timing jitter is 10 fs for Fourier frequencies from 10 Hz to 10 MHz. The main contribution to this integrated jitter comes from the −140 dBc/Hz white noise floor at Fourier frequencies between 1 and 10 MHz. The residual jitter arising from the main components is 3 fs for the frequency divider, 5 fs for the mixer and amplifier, and 9 fs for semiconductor optical amplifier. The jitter at 20 GHz should have approximately the same value. Assuming linear detection and a white noise floor dominated by the optical amplification (SOA), the intrinsic timing jitter could be independent of harmonic, such that the measured timing jitter of the 20 GHz harmonic would also correspond to that of the 40, 60, and 80 GHz harmonics.

Conclusion: We have evaluated the residual phase-noise properties of 20 GHz picosecond optical pulses generated at 1550 nm by a

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modulator-based optical frequency comb generator. Our analysis indicates the resulting harmonics (20, 40, 60, 80 GHz) have low phase noise relative to the input 10 GHz modulation signal. Experimentally, the residual phase noise of the 20 GHz harmonic was measured, and an integrated timing jitter $\leq$10 fs was achieved for Fourier frequencies between 10 Hz and 10 MHz. The measured noise is mainly limited by the optical amplifier's noise. These results imply that the OFCG should be a useful tool for low-noise synthesis and the delivery of precise timing signals in microwave and millimetre-wave photonic systems.

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