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Phase noise analysis of an optical frequency comb using single side-band suppressed carrier modulation in an amplified optical fiber loop

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Abstract: Coherent optical two-tone generation using an optical frequency comb generator based on an amplified optical fiber loop is successfully demonstrated. The observed phase noises in the 100-GHz band are less than −80 dBc/Hz at 1 MHz. This method is suitable for high-speed radio communication based on advanced modulation techniques.

Keywords: radio over fiber, optical frequency comb, phase noise

Classification: Fiber optics, Microwave photonics, Optical interconnection, Photonic signal processing, Photonic integration and systems

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ELectronics EXpress

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1 Introduction

High-speed, high-frequency radio transmission technology has been in high demand for use in next-generation mobile and home local area network communication. As compared with conventional microwave radio, the available bandwidth of more than 5 GHz provides a radio transmission capacity of 10 Gb/s [1, 2, 3]. The frequency region higher thanabove 300 GHz is a promising candidate for the realization of high-capacity, short-distance radio, and therefore, electronic devices for sub-millimeter wave radio have been developed rapidly. However, advanced radio communication technology including multi-level modulation technology, forwhich allows high capacity transmission, has not yet been applied, yet because of its bandwidth, stability of a frequency, and linearity issues.

Radio-over-fiber (RoF) technology based on photonics technology is one of the attractivepossible solutions to these problems. High-speed electronics for baseband modulation and a direct photonic up-conversion technique can provide high-speed radio transmission at the a frequency of 100 GHz and at frequencies greater than 300 GHz [4, 5]. In this case, the quality of the RoF

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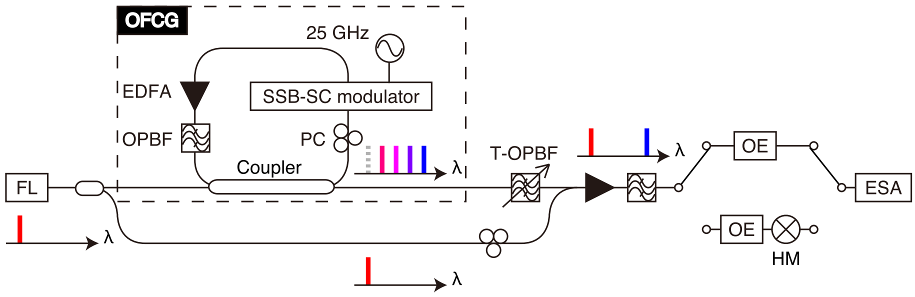

Fig. 1. Experimental setup with schematic drawings of optical spectra.

signals, particularly the stabilization of the center frequency of the radio, plays an important role in coherent detection, because the carrier frequency fluctuation degrades the signal quality and increases the load on digital signal processing (DSP) to compensate for impairments in transmission; additionally, the total energy consumption will increase [6, 7]. For generation of an optical two-tone signal with the frequency separation larger than 100 GHz, that is the RoF signal, an optical frequency comb (OFC) would be a promising candidate. A mode-locked laser can provide a low cost, small footprint, and a wide-band OFC signal [8]. However, thermal and dimensional instabilities of a laser cavity cause the fluctuation of a repetition rate, which corresponds to the frequency. On the other hand, an optical modulation with a continuous-wave laser can provide a frequency-stabilized OFC signal because this stability is based on an electrical synthesizer, whose stability is high enough about several Hz in general, connected to the optical modulator [9]. The OFC signal bandwidth would have less than 1 THz due to the modulator driver issues.

We demonstrated two-tone signal generation using the OFC based on the combination of a frequency shifter and an optical fiber loop [10, 11, 12]. This fiber-loop-based OFC can realize accurately frequency-locked feature with high bandwidth of the OFC signals. The obtained degradation between a single sideband (SSB) phase noise at 25 GHz and 100 GHz was 11.3 dB, which follows the well-known theoretical equation.

2 Experimental setup

Figure 1 sshows our experimental setup. The OFC generator (OFCG) consists of a polarization controller (PC), an optical SSB suppressed carrier (SSB-SC) modulator operated at a frequency of 25 GHz, an erbium-doped optical fiber amplifier (EDFA), and an optical bandpass filter (OBPF). Laser light was emitted by a fiber laser (FL) with a linewidth of 1 kHz and was then directed into the OFCG. The SSB-SC modulator, which was a dual-parallel Mach-Zehnder interferometer modulator, shifted the wavelength of the incident light to the low-frequency side of 25 GHz (Fig. 2 (a)) after polarization was optimized by the PC [13]. The wavelength-shifted optical signal was amplified by the EDFA and then passed through the OBPF both to suppress

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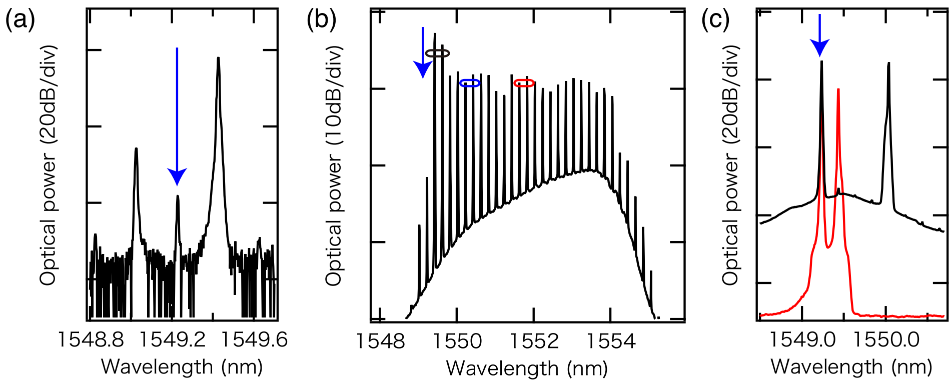

Fig. 2. Optical spectra of (a) SSB-SC modulation, (b) generated OFC, and (c) two-tone signal for 25 GHz (red) and 100 GHz (black) observed before OE conversion. Blue arrows indicate the incident laser wavelength of 1549.2 nm. Colored circles in (b) indicate the components used to observe the phase noise shown in Fig. 3 (a).

the amplified spontaneous emission and to limit the total bandwidth of the OFC. The amplified signal was coupled by the optical coupler to the incident light of the OFCG. Finally, the OFC was generated from the output port of the optical coupler of the OFC (Fig. 2 (b)). One should note that a conventional 2×2 3-dB optical coupler was used as a coupler.

The generated OFCG was sliced by a tunable OBPF, which was tunable for both the center wavelength and the bandwidth, to generate frequency-shifted single tone components. The sliced component was coupled by the laser irradiated by the FL passed through the PC for the optimization of polarization, and thus, an optical two-tone signal was successfully generated (Fig. 2 (c)). The EDFA with the OBPF boosted the two-tone signal by approximately 7 dBm. To evaluate the frequency fluctuation and the SSB phase noise, an optical-to-electrical converter (OE) with a 3-dB bandwidth of 50 GHz converted the two-tone signal to a corresponding electrical signal. An electrical spectrum analyzer (ESA; Agilent Technology E4448A) with an SSB phase noise measurement function was used for evaluation. A harmonic mixer (HA; Agilent Technology 11970 W), with a multiplication number of 18, connected to a uni-traveling carrier photodiode used as an OE converter was used for the measurement in the frequency range of 75–110 GHz.

3 Phase noise measurement

The obtained two-tone spectra with a separation of 25 GHz and 100 GHz are shown in Fig. 2 (c). The observed spurious free dynamic range is greater than 40 dB in both cases. The obtained optical two-tone signal should be coherent because the coherence length of the FL is estimated to be approximately 100 km, which is much longer than the OFCG loop length estimated to be less than approximately 20 m. First, to evaluate the quality of the OFCG, the phase noise between the nearest-neighbor components is examined, as

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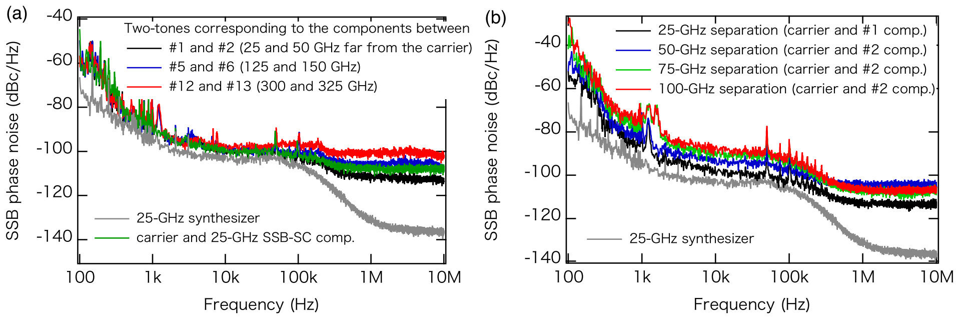

Fig. 3. Observed phase noises for the optical two-tone signals (a) between nearest neighbors of the OFC and (b) corresponding to 25, 50, 75, and 100 GHz. Gray lines indicate the phase noise of the synthesizer operated at 25 GHz for reference. Dark green line in (a) indicates a beat note signal between a carrier component and 25-GHz-shifted SSB-SC modulated component without a fiber loop.

shown in Fig. 3 (a). At frequencies less than 100 kHz, the observed behavior of the phase noise seems similar in each observed component. On the other hand, at frequencies greater than 100 kHz, the phase noise increase when the separation between the observed optical component and the carrier component that is only the FL component increase. This degradation might be caused by the degradation of the signal to noise ratio (SNR) of the two-tone component; however, in practice, the observed SNR degraded because of the increase in the noise component caused by amplified spontaneous emission by the EDFAs in the fiber loop and inputted to the OE convertor; thus, a low-noise EDFA improves the SNR. To some extent, the parasitic peaks might be caused by the spectrum analyzer.

The observed phase noises of the two tones generated by the carrier and the specifically selected optical components are shown in Fig. 3 (b). The phase noises decrease with an increase in the frequency separation. The observed values for 25, 50, 75, and 100 GHz at a frequency of 10 kHz were -98.2, -92.8, -90.1, and -87.9 dBc/Hz, respectively. The theoretical decrease in the phase noise is described by $20 \log m$ (where m is the multiplication number), and thus, the corresponding reductions are estimated to be about 6.0, 9.5, and 12 dB, respectively. These values are in good agreement with the observed differences; the phase noise degradation of the two tones generated by the OFCG matches the theory closely. One should note that the observed phase noises at the offset frequency of 100 Hz were degraded about 10 dB rather than the electrical signal launched into the modulator. The behavior of the phase noise obtained from a beat note between a carrier component and a 25-GHz-shifted SSB-SC modulated signal without a fiber loop seems to be same as the other observed ones. This indicates that that degradation could be caused by the phase rotations of the lightwaves propagating in the fiber loop as well as in the fiber path for the optical carrier component due to a fiber length fluctuation. In addition, a relative intensity noise of the FL

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at low frequency region might cause this degradation. However, for application to the high-speed radio transmission, these low-frequency phase noise components would be negligible.

For example, for 300-GHz signal generation, which corresponds to a multiplication number of 12, the predicted phase noises at 10 kHz and 1 MHz are -71 and -91.4 dBc/Hz, respectively, because the observed phase noise for the 25 GHz signal at 1 MHz was -113 dBc/Hz. It should be noted that the reduction at frequencies greater than 100 kHz could be caused by the EDFA. The phase noise of the two-tone signal immediately after the OFCG might be less than the observed value.

4 Conclusion

We demonstrated high-frequency, two-tone signal generation using an OFCG. The observed phase noise for a 100-GHz signal at 1 MHz is much less than -80 dBc/Hz; thus, the signal can be applied to radio communication using advanced modulation formats such as quadrature-phase-shift-keying and quadrature amplitude modulation with digital coherent detection technique. This method is suitable for both sub-millimeter wave radio communication and terahertz radio communication.

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