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Discussion

W-band RoF transmission based on optical multi-carrier generation by cascading one directly-modulated DFB laser and one phase modulator

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ABSTRACT

We experimentally demonstrate that, adopting an optical multi-carrier source based on cascaded directly-modulated distributed-feedback laser (DML) and phase modulator (PM), any pair of subcarriers spaced by 100 GHz selected from the generated optical subcarriers can be used to generate 100-GHz millimeter-wave (mm-wave) frequency based on remote heterodyning technique, and thus realize 3.125-Gb/s on-off-keying (OOK) signal transmission over a radio-over-fiber (RoF) system at W-band. After 20-km large-effective-area fiber (LEAF) transmission and 2-m wireless delivery, the bit-error ratio (BER) of 1×10^{-9} can be attained when the two selected subcarriers spaced by 100 GHz are simultaneously modulated before remote heterodyning. 1.5-dB power penalty at the BER of 1×10^{-9} is caused by 2-m wireless delivery while almost no penalty is caused by 20-km LEAF transmission. However, because of different path lengths and the quite wide linewidth of the DML, the 3.125-Gb/s OOK signal after the same RoF transmission cannot be recovered when the two selected subcarriers are separated into two different optical paths and only one of them is modulated before remote heterodyning.

1. Introduction

In order to realize the seamless integration of wireless and fiber-optic networks, the wireless links need to be developed to match the capacity of high-speed fiber-optic communication systems, while preserving transparency to bit rates and modulation formats. Recently, the W-band (75–110 GHz), with wider bandwidth and higher frequency, has attracted increasing interest as a candidate radio-frequency (RF) band to provide multi-gigabit wireless links for mobile data transmission [1–11]. It is well known that it is challenging to generate millimeter-wave (mm-wave) frequencies at W-band based on bandwidth-limited electrical components. A more attractive solution for the W-band mm-wave generation would be the employment of photonic techniques, such as remote heterodyning [8–11] and external modulation [12]. Furthermore, photonic mm-wave techniques effectively promote the seamless integration of wireless and fiber-optic networks and can be well applied to the optical wireless integration system, such as the radio-over-fiber (RoF) system. It is well known that remote heterodyning is one kind of simple and cost-effective photonic mm-wave technique, in which, two optical carriers with different wavelengths are generated from two individual lasers and then beat together to generate a specific mm-wave frequency. However, in an optical mm-wave multiplexing system [13], multiple mm-wave frequencies are needed at the same time, which requires much more optical carriers. Thus, an optical multi-carrier source can be used for the mm-wave frequency generation to avoid the requirement for a large number of lasers [14]. There are several different methods to realize optical multi-carrier generation. The conventional method based on mode-locked laser (MLL) inherently suffers from cavity complexity and does not offer the free spectral range (FSR) tunability [15]. The method based on external optical modulation, such as in-phase/quadrature (I/Q) modulator combined with recirculating frequency shifter (RFS) [16–19], cascaded intensity modulator (IM) and phase modulator (PM) [20,21], and PMs only [22], can realize wavelength tunable multi-carrier generation but have the disadvantages of large insertion losses and expensive component cost. The method based on the gain switching of discrete-mode laser and distributed feedback (DFB) laser makes full use of the inherent simplicity of direct modulation and can realize cost-efficient multi-carrier generation with a tunable FSR [23–27]. Moreover, PM can be further introduced to provide spectral expansion. However, a master–slave configuration is usually needed for the last method to provide external injection. Recently, we have experimentally demonstrated a potentially simple and cost-effective optical multi-carrier source based on cascaded directly-modulated DFB laser (DML) and PM driven by synchronous sinusoidal RF signal, which does not require an extra

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continuous-wavelength (CW) tunable laser to provide external injection and can successfully generate 16 optical subcarriers with frequency spacing of 12.5 GHz and power difference less than 3 dB [27].

In this paper, adopting the optical multi-carrier source based on cascaded DML and PM proposed in [27], we experimentally demonstrate any pair of subcarriers spaced by 100 GHz selected from the generated optical subcarriers can be used to generate 100-GHz mm-wave frequency based on remote heterodyning technique, and thus realize 3.125-Gb/s on-off-keying (OOK) signal transmission over a RoF system at W-band. After 20-km large-effective-area fiber (LEAF) transmission and 2-m wireless delivery, the bit-error ratio (BER) of 1×10^{-9} can be attained when the two selected subcarriers spaced by 100 GHz are simultaneously modulated before remote heterodyning. 1.5-dB power penalty at the BER of 1×10^{-9} is caused by 2-m wireless delivery while almost no penalty is caused by 20-km LEAF transmission. However, because of different path lengths and the quite wide linewidth of the DML, the 3.125-Gb/s OOK signal after the same RoF transmission cannot be recovered when the two selected subcarriers are separated into two different optical paths and only one of them is modulated before remote heterodyning.

2. Theoretical analysis for the cascaded DML and PM scheme

It is well known that sinusoidal phase modulation of a narrow-band continuous-wavelength (CW) laser can create a frequency comb with high repetition rate, tunable frequency spacing and stable optical central frequency. As shown in Fig. 1(a), when one PM driven by a sinusoidal RF signal at f_s is used to modulate the CW lightwave at f_c, the output electrical field of the PM can be expressed as

$$E_{out}(t) = E_0\exp(j2\pi f_c t)\exp[jR\sin(2\pi f_s t)] = K\sum_{n=-\infty}^{\infty} J_n(R)\exp[j2\pi(f_c+nf_s)t]. \quad (1)$$

where E_0 is the amplitude of the electrical field, J_n is the first kind Bessel function of order n, and R is the modulation index of the PM. The disadvantage for comb generation based on only PM is quite poor spectral flatness. Furthermore, the limited driving voltage of PM and the limitation of electrical amplifiers (EAs) significantly limit the modulation index of PM and the number of the generated optical subcarriers.

In order to overcome the disadvantages of the PM-only scheme, we propose the novel cascaded PM and DML scheme, just as shown in Fig. 1(b). When biased at a large DC and driven by a sinusoidal RF signal at f_s, the output electrical field of a DML at f_c can be expressed as [28]

$$E_{out1}(t) \approx E_0[1 + R_1\sin(2\pi f_s t)]\exp(j2\pi f_c t). \quad (2)$$

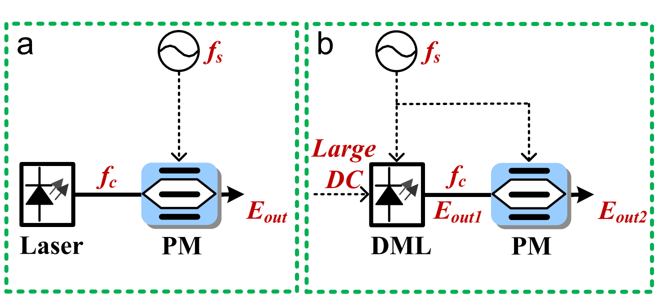

Fig. 1. Schematic diagram of comb generation based on (a) PM-only and (b) cascaded DML and PM.

where R_1 is the modulation index of the DML and defined by the ratio of the RF driving amplitude to the bias current for the DML. Here, the inherent chirp from the DML is largely removed and can be neglected due to the adoption of the large DC bias [29]. The other benefits of large bias of the DML are high output power, wide modulation bandwidth, stable single-mode operation and low timing jitter. Thus, the output electrical field of the PM driven by the synchronous sinusoidal RF signal at f_s can be expressed as

$$\begin{aligned} E_{out2}(t) &\approx E_0[1 + R_1\sin(2\pi f_s t)]\exp(j2\pi f_c t)\exp[jR_2\sin(2\pi f_s t)] \\ &= E_0\sum_{n=-\infty}^{\infty} J_n(R_2)\exp[j2\pi(f_c+nf_s)t] \\ &\quad - jE_0\frac{R_1}{2}\sum_{n=-\infty}^{\infty} J_n(R_2)\exp\{j2\pi[f_c+(n+1)f_s]t\} \\ &\quad + jE_0\frac{R_1}{2}\sum_{n=-\infty}^{\infty} J_n(R_2)\exp\{j2\pi[f_c+(n-1)f_s]t\}. \end{aligned} \quad (3)$$

where R_2 is the modulation index of the PM and defined by the ratio of the RF driving amplitude to the half-wave voltage V_{pi} for the PM. Compared to Eq. (1), the right second and third terms of Eq. (3) can flatten the amplitude of the generated optical subcarriers spaced at f_s. Furthermore, the advantages of DML, such as low cost, compact size, low power consumption and so on, make the cost and integration of our proposed scheme much more efficient [30].

3. Experimental setups and results for optical multi-carrier generation and W-band RoF transmission based on the cascaded DML and PM scheme

Two different W-band RoF systems are proposed and experimentally demonstrated in this section. For both systems, two subcarriers spaced by 100 GHz are selected from the generated subcarriers based on cascaded DML and PM and then used to generate 100-GHz mm-wave frequency based on remote heterodyning. What is different is that, two selected subcarriers are simultaneously modulated before remote heterodyning for the first system while only one of two selected subcarriers is modulated before remote heterodyning for the second system.

3.1. The first W-band RoF system when two selected subcarriers are simultaneously modulated

Fig. 2 shows the experimental setup for the first W-band RoF system based on the cascaded DML and PM scheme. For optical multi-carrier generation, a 12.5-GHz sinusoidal RF signal is first equally split into two branches by a power divider. Next, one branch is power amplified to 24 dBm and used to drive the DML, while the other is power amplified to 30 dBm and used to drive the PM. The phase shifter (PS) before the PM is used to synchronize the two branches. The polarization-maintaining erbium-doped fiber amplifier (EDFA) between the cascaded DML and PM is used to compensate for the modulation loss and the insertion loss.

The DML is a commercially available DFB laser (NEL NTT NLK1551SSC) and has 74-mA DC bias, 9.3-dBm average output power and 3-dB bandwidth of over 20 GHz. Fig. 2(a) shows the output optical spectrum (0.01-nm resolution) of the DML. The optical spectrum is asymmetrical at 1537.7-nm central wavelength due to the inherent chirp from the DML [30]. The PM has a half-wave voltage of 4.2 V at 12.5-GHz RF driving frequency, and a RF driving amplitude of about 10 V at 50-Ω input resistance, which means that the modulation index R_2 is 2.4. Fig. 2(b) shows the optical spectrum (0.01-nm resolution) after the cascaded DML and PM. 16 optical subcarriers with 12.5-GHz frequency spacing are