Article

Self-Start Multi-Wavelength Laser Source with Tunable Delay-Line Interferometer and Optical Fiber Reflector for Wireless Communication System

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Abstract: The radio-over-fiber (RoF) technique has gained a lot of interest recently, as the millimeter-wave signals can be generated and delivered in the optical domain with the advantages of low attenuation, high capacity, and being free from electromagnetic noise interference (EMI). In this paper, we propose and experimentally prove a self-start multi-wavelength laser source based on a distributed feedback laser diode (DFB-LD) for the RoF transport system. The self-start multi-wavelength laser source generates stable laser power with less than 0.18 dB power fluctuation and exhibits good stability. In order to estimate the transmission performance, data is externally modulated onto the multi-wavelength by a reflective semiconductor optical amplifier (RSOA) and transmitted through single-mode fiber (SMF). The experimental result proves that the proposed RoF transport system achieves error-free transmission and clear eye diagrams.

Keywords: radio-over-fiber; multi-wavelength laser; wireless communication system

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1. Introduction

Performance-boosting of bandwidth and long-distance coverage are currently the most pressing concerns for end-to-end connection and quality of service in both wired and wireless broadband access [1–5]. Thus, the goals of transmitting and receiving more data as enhanced Mobile Broadband (eMBB), interconnecting millions of devices at once by means of massive machine type communication (mMTC), and increasing responsiveness by ultra-reliability and low latency communication (URLLC) for fifth-generation (5G) new radio (NR) next-generation communication systems are considerably studied [6–13]. The radio-over-fiber (RoF) technique, which can generate and deliver millimeter-wave signals in the optical domain, is a good candidate for next-generation communication systems due to the advantages of fiber such as high capacity, low attenuation, lightweight, and being free from electromagnetic noise interference (EMI) [14–18]. In the RoF transmission system, the desired signal can be optically upconverted to a higher frequency band by means of selecting the specific wavelength. Hence, the multi-wavelength generation technique plays an important role in the RoF system. Conventional multi-wavelength schemes use an array of laser sources, external modulators, and local oscillators. However, adding multiple devices in the central station increases the overall cost of the transmission system. In [19–21], semiconductor optical amplifiers (SOAs) and erbium-doped fiber amplifiers (EDFAs) are utilized as gain mediums to generate multi-wavelengths. Although EDFA has the characteristics of a flatter gain spectrum, lower polarization-dependent gain, and higher saturation power, it has a strong line broadening and cross-saturation at room temperature. Hence, it is challenging to secure stable multi-wavelength lasing at room temperature using

EDFA. In [22], an SOA-based ring laser using coupled ring cavities is used to generate multi-wavelength. However, its performance is limited by polarization, and it is difficult to control the cavity.

Optoelectronic oscillators (OEOs) have attracted much attention owing to the characteristics of high-quality factors, extremely low noise, excellent performance even at higher frequencies, and other characteristics that are not achieved with electronic oscillators. Conventional OEO schemes require external modulators [23–25] and continuous-wave lasers. However, an external modulator causes high insertion loss due to its low modulation efficiency. Therefore, the conventional OEO scheme needs three electrical amplifiers [23].

In this research, a self-start multi-wavelength laser source is proposed and experimentally demonstrated, achieved by directly modulating a commercially available distributed feedback laser diode (DFB-LD) without any local oscillator. The self-start multi-wavelength laser source is based on a self-starting optoelectronic oscillator [23]. A double-pass filter composed of an optical circulator, tunable delay line interferometer (TDLI), and an optical fiber reflector (OFR) is proposed to enhance the tone-to-noise ratio (TNR). A tunable filter (OTF) is used to choose wavelengths for baseband or wireless signal. A reflective semiconductor optical amplifier (RSOA) modulates data signals and is sent across a 25 km single-mode fiber (SMF). The system performance is verified using clear eye diagrams and error-free signal transmission.

2. Experimental Setup and Results

The schematic structure of the proposed self-start multi-wavelength laser source for wireless networks is shown in Figure 1. The demultiplexer selects two wavelengths from the multi-wavelength laser source for each channel [17]. The desirable data streams are modulated onto the selected wavelengths by the RSOA. Then, the multiplexer combines all the wavelengths before the SMF transmission. After fiber transmission, the demultiplexer splits the received optical signal into different base stations (BS) and a photodetector (PD) is employed to convert the optical signal into an electrical signal before being emitted by the antenna for wireless transmission.

Figure 1. Schematic illustration of the self-start multi-wavelength laser for RoF transport systems for wireless applications (RSOA: reflective semiconductor optical amplifier, BS: base station, and SMF: single-mode fiber).

The detailed configuration of the proposed self-start multi-wavelength laser source is depicted in Figure 2. The lightwave emitted from the DFB laser is launched to port 1 of the optical circulator. Then, the lightwave output from port 2 of the optical circulator (OC) is routed to a tunable delay interferometer and reflected back to the OC by the optical fiber reflector. Subsequently, port 3 of the OC passes the lightwave to a 1×2 optical coupler with a 90/10 ratio. The branch with a 10% power ratio is connected to the optical spectrum analyzer for the monitor, while the other branch sends the lightwave to a PD (PP-10G) for optical-to-electrical conversion. The electrical signal is amplified by an electrical

amplifier (EA), filtered by a high-Q bandpass filter (BPF), and then inserted into the DFB laser for direct modulation after being amplified again by the second EA. After several rounds of the above-mentioned operation, the self-start multiwavelength laser based on the OEO structure is generated. In the optical path, TDLI is employed to reshape the multi-wavelength, and the OFR reflects the lightwave back to the TDLI for the second reshaping to boost the tone-to-noise ratio (TNR). In the electrical path, the first EA is utilized to compensate for the loss caused by the optical-to-electrical conversion, and the second EA is used to boost the electrical signal before being fed into the DFB. The 3-dB bandwidth of the high-Q BPF is 10 MHz, and the Q factor is calculated to be 995.3.

Figure 2. Experimental setup of OEO-based multi-wavelength generation (DFB: distributed feedback laser, TDLI: tunable delay interferometer, OFR: optical fiber reflector, PD: photodetector, EA: electrical amplifier, High Q BPF: High-Q bandpass filter).

The radio-frequency (RF) tone generated by the OEO structure is measured by the electrical analyzer as illustrated in Figure 3. By adjusting the gain of the second EA, the output power of the RF tone can be tuned to modulate the DFB laser for manipulating the output number of the wavelength of the self-start multi-wavelength laser source. As demonstrated in the inset of Figure 3, the numbers of multiwavelength are 3, 5, and 10 when the power of the inserted RF tone is 6 dBm, 10 dBm, and 20 dBm, respectively.

Figure 3. A generated RF signal's output spectrum and laser output vs. RF power.

When the power of RF tone inserted into the DFB laser increases, the number of the generated multi-wavelength increases. In contrast to the number of wavelengths, the tone-to-noise ratio (TNR) decreases. Therefore, to enhance the TNR, the TDLI is deployed to reshape the multi-wavelength. Figure 4 demonstrates the measured spectra and the measuring setup of two different structures of TDLI. For the first structure, OSA captures the optical spectrum of the broadband light source after passing the TDLI for single filtering, as the red line illustrates in Figure 4. The signal-to-noise ratio (SNR) of single filtering is only 10 dB. To enhance these SNR results, a second structure with double filtering is proposed. The broadband light source is launched to port 1 of OC and then routed to the TDLI for first filtering.

Figure 4. The broadband source with single-pass and double-pass filters.

The filtered broadband light source is reflected by the OFR and inserted back to the TDLI again for second filtering. After, the lightwave output from port 3 of OC is measured by the OSA, as the red line shows in Figure 4.

Compared to single filtering, the double filtering structure, whose SNR is 16 dB, exhibits better performance. A round trip through the same tunable delay interferometer reduces the linewidth of the transmission peaks and is effective in suppressing spontaneous noise. The optical spectra of the self-start multi-wavelength laser, with and without the double filtering technique, are demonstrated in Figure 5. Without double filtering, the power fluctuation is about 7.5 dB and the TNR is 7 dB. By employing double filtering, the TNR has been improved to 18 dB.

As the stability of the self-start multi-wavelength laser is another important factor, the optical power of 1537.768 nm, 1537.848 nm, 1537.928 nm, 1538.004 nm, 1538.084 nm, 1538.16 nm, 1538.24 nm, 1538.32 nm, 1538.396 nm, and 1538.476 nm are chosen to be monitored every 2 min as illustrated in Figure 6. Among all wavelengths, the power fluctuation is less than 0.18 dB, showing good stability of the proposed scheme.

The experimental configuration of the RoF transport system based on the proposed self-start multi-wavelength laser is illustrated in Figure 7. In the central office, the multi-wavelength laser is externally modulated by the data via RSOA. At the transmission end, we use semiconductor optical amplifiers as modulators, in the output spectrum current region of RSOA is between 60~80 mA; we also fixed the RSOA bias current at 70 mA as an application. Subsequently, the modulated lightwave is amplified by an EDFA before the OTF. The OTF is utilized to select the specific wavelength to allocate the RF frequency. After 25 km SMF transmission, the PD converts optical components into an electrical signal and up-converts the signal to a higher frequency band based on the wavelength spacing of

the selected wavelength at the BS. The optical signals displayed on OSA and the electrical signal were transmitted to the electrical spectrum analyzer and bit error tester.

Figure 5. Output optical and TNR spectrum with and without a double-pass filter.

The bit error rate (BER) curve and eye diagram of 155 Mbps and 622 Mbps signals after back-to-back (BTB) within 25 km SMF distance data transmissions are illustrated in Figure 8, where we selected only one wavelength optical spectrum of the multi-wavelength laser. Figure 8 shows a BER and eye diagram with different modulation data. As demonstrated in Figure 8, the eye diagrams are clear and open. The eye diagrams of 155 Mbps and 622 Mbps signals were captured at -22.5 dBm and -21.5 dBm, respectively. The received optical power is measured using power monitor-attenuators (EigenLight Corporation). The measured point is before the PD. The table in Figure 8 shows the power penalty in different data rates. The power penalty of 155 Mbps and 622 Mbps signals were 0.1 dB and 0.2 dB, respectively. The power penalty for 622 Mbps signal transmission was relatively higher due to the effect of fiber dispersion.

Figure 6. Cont.

Figure 6. Output power stability for the selected wavelengths.

The optical spectra of the multi-wavelength laser and the selected two wavelengths are illustrated in the top inset of Figure 9. The wavelength spacing of the two selected wavelengths is about 0.08 nm, and thus the 155 Mbps data carried by these two optical tones is upconverted to 9.953 GHz. The bottom inset of Figure 9 demonstrates the measured electrical spectrum of the 155 Mbps data. The center frequency of the signal is located at 9.953 GHz and the eye diagram is also clear. The RF signal is generated by the two-tone interference method [17]. The SNR is over 20 dB, which may support future wireless broadband access applications. Moreover, the eye diagram was captured at -16.5 dBm. The frequency of the RF signal depends on the central frequency of the high-Q BPF; we can use different central frequencies of the high-Q BPF for different applications [24]. To further analyze the performance of the system, the bit error rate versus different optical received power was measured. Error-free is achieved while the optical received power is larger than -16.5 dBm.

Figure 7. The architecture of the self-start multi-wavelength laser for RoF transmission.

Figure 8. Comparison of BER curve and eye diagram for BTB and 25 km transmission.

Figure 9. The measured BER, eye diagram, and electrical and optical spectrum on two selected wavelengths.

3. Conclusions

A self-start multi-wavelength laser source based on the OEO structure is proposed and proven in this paper. This proposed multi-wavelength laser source could be packaged in a smaller module using optical waveguide techniques to reduce power loss and simplify the complexity of OEO devices [24]. By employing the double filtering structure, the TNR value of 18 dB and a power fluctuation below 0.18 dB among 10 wavelengths are achieved. To estimate and determine the performance of the proposed scheme, OTF is deployed to select one and two wavelengths to be modulated by the input data through the RSOA. After SMF transmission, the optical signals are converted to electrical signals, which are estimated in terms of bit error rate and eye diagram. According to the experiment

results, both one and two selected wavelengths can achieve error-free transmission and clear eye diagrams.

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