Photonic generation of ultrawideband signals based on a gain-switched semiconductor laser with optical feedback

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A simple photonic approach to generate ultrawideband (UWB) pulse signals utilizing a gain-switched semiconductor laser with optical feedback is proposed and demonstrated. The RF spectrum of the generated chaotic UWB signals has a $-10\,\text{dB}$ bandwidth of 9 GHz and central frequency of 6.6 GHz (fractional bandwidth of 155%), which is consistent with the Federal Communications Commission indoor mask. The central frequency and $-10\,\text{dB}$ bandwidth can be tuned by adjusting the bias current and feedback strength of the semiconductor laser. After transmission through a 30 km single-mode fiber, the spectrum shape of the chaotic UWB signals is almost unaffected by the chromatic dispersion of the fiber. © 2013 Optical Society of America

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1. Introduction

Ultrawideband (UWB) technology is extensively used in high-speed wireless communication, wireless sensor networks, through-the-wall radar, intelligent transportation, and precise positioning due to its high-speed, immunity to multipath fading, low power consumption, good penetrability, and accurate positioning function [1–3]. Unfortunately, UWB signals can only transmit over a short distance from a few meters to tens of meters. In order to extend the transmission distance and combine the existing fixed wired networks with the wireless wide-area infrastructure, UWB over fiber has been proposed [4]. The generation of UWB signals in the optical domain is highly desirable because it can avoid extra electrical-to-optical conversion and electromagnetic interference.

Many optical methods of UWB signal generation have been proposed in the past few years. Pan and Yao used a phase modulator and a reconfigurable asymmetric Mach–Zehnder interferometer to generate polarity-switchable UWB Gaussian pulses [5]. In [6], Su and co-workers utilized a double parallel Mach–Zehnder interferometer to generate UWB signals. Zhang and co-workers utilized cascade Mach–Zehnder modulators to modulate a continuous optical wave when generating UWB signals [7]. In [8], Capmany and co-workers employed an N-tap
reconfigurable microwave photonic filter fed by a laser array to generate UWB pulses. Lin and co-workers used a highly nonlinear photonic crystal fiber to generate UWB signals [9]. Wong and co-workers utilized multiple cross phase modulation (PM) and multiple PM-intensity modulation conversion in a highly nonlinear fiber to generate UWB pulse signals [10]. LaRochelle and co-workers demonstrated a prototype for a UWB waveform generator based on optical pulse shaping [11]. In [12], Yu et al. used the relaxation oscillations of a semiconductor laser to generate UWB signals. Feng et al. utilized polarization-maintaining fiber Bragg grating as a discriminator to generate UWB signals [13]. Xie and co-workers employed synchronous polarization modulation and birefringence time delay to generate multiband UWB pulse signals [14]. Juan and Lin achieved the optical UWB signals by using an optical pulse-injected semiconductor laser [15]. Zhu and co-workers experimentally demonstrated photonic approaches to generating the UWB pulses based on a negative coefficient two-tap microwave photonic filter [16] and four-wave mixing in a highly nonlinear fiber [17]. The above research focused on generating UWB Gaussian pulses that complied with the FCC indoor wireless communication spectral mask, where the monocycle, doublet, and triplet pulses with broad bandwidths were generated.

In addition, Khan et al. obtained an UWB arbitrary radio frequency waveform using a silicon photonic chip-based spectral shaper, which realized a wide range of tunable central frequencies [18]. Peled et al. proposed a noise-like approach to generate UWB waveforms with a controllable spectrum bandwidth and tunable central frequency based on stimulated Brillouin scattering amplified spontaneous emission [19]. Li and Yao generated continuously tunable chirped microwave waveforms based on a temporal interferometer incorporating an optically pumped linearly chirped fiber Bragg grating [20].

In previous works [21, 22], we utilized a chaotic laser and external electroabsorption modulator to generate UWB pulse signals. However, the schemes were somewhat complex, and the generated chaotic UWB signals had a low extinction ratio. In this paper, we propose and demonstrate a very simple photonic and economical method to generate chaotic UWB pulse signals based on a gain-switching technique of a directly modulated semiconductor laser with optical feedback. Compared with our previous works [21, 22], this scheme does not need an additional wideband modulator, which makes the system simple and inexpensive. Furthermore, the generated chaotic UWB pulse’s signal not only has a controllable spectrum bandwidth and tunable central frequency, but it also has a high extinction ratio, which indicates that the signal can be transmitted with a low bit error rate in the UWB-over-fiber communication system. Moreover, compared with utilizing only a gain-switched laser to generate UWB signals [23], the chaotic UWB pulse’s signal generated by this method has a nondiscrete power spectrum, so the problems caused by the discrete line spectral components can practically be neglected.

2. Experiments

Figure 1 illustrates the experimental setup of the chaotic UWB pulse’s generation. A commercial distributed feedback laser diode (DFB-LD) subject to optical feedback is used as the chaotic laser source. The output light of the DFB-LD is divided by a 50/50 fiber coupler into two paths: one is used as output and the other as feedback light. The power and polarization state of the feedback light are adjusted by a variable attenuator (VA) and polarization controllers (PC1 and PC2), respectively. By directly modulating the DFB-LD with a random code sequence, we can obtain the chaotic UWB pulses. The chaotic optical pulse sequence is converted into a chaotic UWB radio pulse sequence via a 45 GHz bandwidth photodetector (New Focus 1014). A 6 GHz bandwidth oscilloscope (LeCroy SDA 8 Zi-A), a 26.5 GHz bandwidth spectrum analyzer (Agilent N9010A), and an optical spectrum analyzer (Agilent 86140B) are used to measure the waveforms, RF spectrum, and optical spectrum of the chaotic UWB pulse signals, respectively.

In the experiments, the center wavelength of the DFB-LD is stabilized at 1549.572 nm with a 0.2 nm linewidth (at −20 dB) by a precise temperature controller. The threshold current is 16 mA. The length of the feedback cavity is 5.6 m. The peak-to-peak value of the random code sequence is 400 mV, which can realize gain switching of the laser.

In Fig. 2, we demonstrate a typical experimental result of the chaotic UWB pulse sequence with rate of 960 Mb/s that was achieved at the following laser parameters: bias current of 32 mA and feedback power of −4 dBm. As shown in Fig. 2(a), the RF spectrum of the chaotic UWB signal (blue line) is compliant with the FCC spectral mask for indoor communications. In detail, the central frequency is about 6 GHz and the −10 dB bandwidth is 9.6 GHz, which means a fractional bandwidth of about 155%.

The time series of a chaotic UWB signal displayed in the bottom map of Fig. 2(b) is measured by using a 6 GHz oscilloscope. Although this means that the signals were low-pass filtered by the front end of the oscilloscope, we can still estimate that the chaotic

![Fig. 1. Experimental setup of the chaotic UWB pulse generation. DFB-LD, distributed feedback laser diode; RNG, random number generator; PC, polarization controller; OC, optical circulator; VA, variable attenuator; ISO, isolator; EDFA, erbium-doped fiber amplifier; SMF, single-mode fiber; PD, photodetector; OSC, oscilloscope; OSA, optical spectrum analyzer; ESA, electronic spectrum analyzer.](image-url)
UWB pulse sequence within the 4.0 ns duration comprises about 20 pulses with a FWHM of about 100 ps, as shown in the top map of Fig. 2(b). Since adopting the gain-switched modulation, we obtain a high extinction ratio UWB pulse signal, which indicates the UWB-over-fiber communication system employing this UWB signal can achieve a low bit error rate transmission.

Furthermore, we investigate the effects of a laser’s bias current and feedback strength on the −10 dB bandwidth and central frequency of the chaotic UWB pulses. In the experiments, we set the feedback strength at −4 dBm and the modulation rate at 960 Mb/s, and then we measure the RF spectrum with different bias current. As displayed in the triangles and circles, respectively, in Fig. 3, the −10 dB bandwidth increases from 5.6 to 9.6 GHz, and the central frequency raises from 3.8 to 6.6 GHz as the bias current increases from 18 to 32 mA. As described in Fig. 4, when the bias current is fixed on 32 mA, the −10 dB bandwidth increases from 7.8 to 9.6 GHz, and the central frequency shifts from 4.0 to 6.6 GHz as the feedback strength increases from −14 to −4 dBm. For a further increase of the bias current or the feedback strength, the −10 dB bandwidth and central frequency continue increasing, but the RF spectrum profile of the generated chaotic UWB signals exceeds the limit of the FCC indoor mask.

We inject the optical UWB signal shown in Fig. 2 separately into several single-mode fibers (SMFs) with different lengths to examine the transmission performance. Note that the optical pulses were amplified by an erbium-doped fiber amplifier (EDFA) before transmission. Figure 5 shows three RF spectra of 10.14, 23.94, and 34.08 km after being transmitted through fibers. It can be found that the power spectrum shape has slight changes, and the signals’ energy has only a downward shift due to the transmission loss through a SMF, which means the generated chaotic UWB pulses have good tolerance to fiber
dispersion. Additionally, the discrete spectrum lines do not appear in the RF frequency domain, which means that the problems caused by the discrete line spectral components could be neglected totally. Otherwise, we should optimize the modulation formats in order to avoid discretization, as mentioned in [24].

3. Discussion

We also discuss the influence of the modulation rate on the −10 dB bandwidth and central frequency of the chaotic UWB pulses. As shown in Fig. 6, when the bias current is 32 mA and the feedback strength is −4 dBm, the −10 dB bandwidth increases a little with the modulation rate, and the central frequency almost has no changes, which is due to the chaos modulation characters, as mentioned in [25].

When we modulate the chaos with the pulse sequence, the RF spectrum of the obtained UWB radio pulses will be the same as that of the original chaos, and it be independent of the pulse duration $T$ when $T > 1/(2\Delta F)$, where $\Delta F$ is the bandwidth of the original chaotic signal [25].

In this paper, the chaotic UWB pulse signals are generated by directly modulating the semiconductor laser with optical feedback. Compared with the RF spectrum in [26], we use a gain-switching technique, and the obtained chaotic UWB pulses signal’s spectrum is consecutive and smooth.

Moreover, the DFB-LD with optical feedback is directly modulated by a RNG with a random code sequence and then the chaotic UWB pulses corresponding to the random code sequence can be obtained. That means, by this gain-switched modulation technique, we can implement the signal coding. The direct current-modulated semiconductor laser with optical feedback has rich dynamic characteristics, such as periodic oscillation, low-frequency fluctuation, and chaos [26–28]. Our study has been restricted to the case of the feedback strength level (in the range of −14 to −4 dB), bias current level (in the range of 1.1–2.0 $I_{th}$), and modulation rate level (in the range of 240–960 Mb/s). If we extend the restriction of the three parameters, the output will transit from chaotic oscillation to other dynamic characteristics.

4. Conclusion

In this paper, we propose and demonstrate a simple photonic scheme to generate UWB signals utilizing a chaotic semiconductor laser with gain-switching modulation. The chaotic UWB pulses at 960 Mbit/s with a fractional bandwidth of 155% and a central frequency of 6.0 GHz are experimentally achieved in the optical domain. Furthermore, by controlling the bias current and feedback strength of the semiconductor laser, the chaotic UWB signals’ central frequency and −10 dB bandwidth are controllable in a certain range. Moreover, the spectral shape has almost no changes when the photonic UWB signal transmits through a long SMF, which means the optical UWB signal in our method has good tolerance to fiber dispersion.

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