Optical ultrawideband monocycle pulse generation based on cross-gain modulation in a semiconductor optical amplifier

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A novel method for generating ultrawideband (UWB) monocycle pulses based on cross-gain modulation (XGM) in a semiconductor optical amplifier (SOA) is proposed and experimentally demonstrated. Thanks to the XGM in the SOA, a pair of polarity-reversed optical Gaussian pulses is generated at the output of the SOA, to which a Gaussian pulse pump and a continuous-wave probe are applied. The two polarity-reversed optical pulses are then time delayed by two cascaded fiber Bragg gratings to introduce a time delay difference. A UWB monocycle pulse with a full width at half-maximum of 48 ps and a fractional bandwidth of 188% is generated at the output of a high-speed photodetector. © 2006 Optical Society of America

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Ultrawideband (UWB) is a fast emerging technology that has recently attracted considerable interest for its applications in short-range, high-capacity wireless communication systems and sensor networks, thanks to advantages such as a very high data rate, low power consumption, and immunity to multipath fading.[1–3] The Federal Communications Commission (FCC) of the U.S. has approved the unlicensed use of the UWB from 3.1 to 10.6 GHz with a power density lower than −41.3 dBm/MHz (FCC, part 15).[1]

Most of the approaches proposed for generating UWB signals with characteristic monocycle or doublet waveforms are implemented mainly by using electronic circuits in the electrical domain.[4–7] To distribute UWB signals over a longer distance, state-of-the-art optical fiber with extremely low loss is considered an excellent candidate for a transmission medium. Therefore the generation and distribution of UWB signals directly in the optical domain has been a topic of interest recently.[8–11] Kawanishi *et al.*[8] proposed to generate UWB doublets in the optical domain by using a specially designed frequency-shift-keying modulator that consists of four optical phase modulators with three electrodes. Lin *et al.*[9] proposed a hybrid system for generating UWB monocycle signals. In the proposed system a gain-switched Fabry–Perot laser diode is used to generate an optical pulse train; a UWB monocycle signal is then produced in the electrical domain by a microwave differentiator. Recently, Zeng and Yao[10] proposed to generate UWB signals by using an optical phase modulator in combination with a length of single-mode fiber (SMF). Thanks to the chromatic dispersion of the SMF, the phase-modulated (PM) signal is converted to an intensity-modulation (IM) signal when it is distributed over the SMF. The PM–IM conversion has a frequency response equivalent to a bandpass filter, which is used to shape the spectrum profile of a Gaussian pulse train, leading to the generation of a UWB doublet at the end of the SMF. In Ref. 11, instead of a long SMF, a fiber Bragg grating (FBG) is employed as a frequency discriminator to perform PM–IM conversion. UWB monocycle or doublet signals can be generated by altering the location of the optical carrier at the linear or the quadrature slopes of the FBG spectral response.

In this Letter we propose and demonstrate a novel and simple method for generating UWB monocycle pulses based on cross-gain modulation (XGM) in a semiconductor optical amplifier (SOA). In this system an optical Gaussian pulse pump and a continuous-wave (CW) probe are applied to the SOA. Thanks to the XGM in the SOA, a pair of polarity-reversed optical Gaussian pulses is generated at the output of the SOA. The two polarity-reversed optical pulses are then time delayed by two cascaded FBGs to introduce a time-delay difference. When the physical spacing between the two FBGs and their reflectivities are properly designed, a monocycle pulse with the required design parameters is generated. The proposed system is experimentally demonstrated. A UWB monocycle pulse train with a full width at half-maximum (FWHM) of 48 ps and a fractional bandwidth of 188% is generated.

The basic idea of this approach is to generate a pair of polarity-reversed pulses at different wavelengths with an appropriate time delay difference between the pulses. The XGM effect in an SOA is used to generate the polarity-reversed pulses. In the proposed approach, when a high-power pulsed pump light is injected into the SOA, the variation of the pump power modulates the carrier density of the SOA so that the gain of the SOA varies inversely with the input laser power. If a CW probe light is injected into the SOA with the pump, the power of the probe light will vary inversely with the pump power, and a pair of polarity-reversed pulses is generated, with one pulse at the pump wavelength and the other at the probe wavelength, as shown in Figs. 1(a) and 1(b). Since the polarities of the pump and the probe pulses are reversed, a direct detection of these two pulses at a photodetector (PD) would lead to a cancellation of

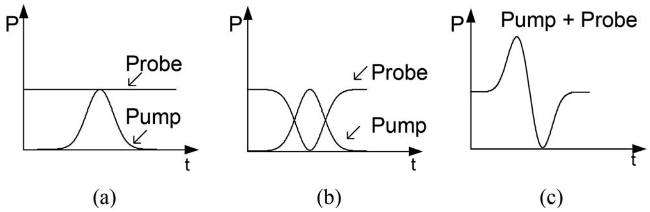

Fig. 1. Principle of the proposed monocycle generation system. Optical power of (a) the input pump and probe and (b) the pair of polarity-reversed pulses at the output of the SOA. (c) Monocycle generated by introducing a time delay difference between the two polarity-reversed pulses.

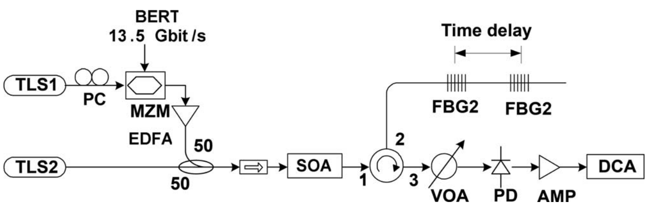

Fig. 2. Experimental setup for UWB monocycle generation. PC, polarization controller; AMP, amplifier.

the two pulses. However, if a proper time-delay difference is introduced between the two pulses, a new pulse that has a shape of a monocycle, as shown in Fig. 1(c), is generated. The pulse width of the monocycle can be controlled by altering the time-delay difference.

An experiment is carried out to verify the proposed approach. The experimental setup is shown in Fig. 2. Two CW tunable laser sources, TLS1 and TLS2, serving, respectively, as the pump and the probe, are used in the system. The output of TLS1 is externally modulated by an electrical data sequence via a Mach–Zehnder modulator (MZM). For all-optical UWB generation, TLS1 and the MZM can be replaced with a pulsed laser source, such as a mode-locked laser. Then a CW probe from TLS2 and the pulsed optical sequence are applied to the SOA via a 3 dB coupler. At the SOA, because of the XGM, the intensity of the probe light is modulated by the pump pulse. A pulse with a shape similar to the pump pulse but with a reversed polarity is generated at the probe wavelength. To obtain a UWB monocycle, a time-delay difference between the two polarity-reversed pulses needs to be introduced. It is realized in the experimental system by using two uniform FBGs (FBG1 and FBG2). The central wavelengths of the two FBGs are chosen to be identical to the wavelengths of the probe and the pump. The time-delayed pulses are then detected at the PD; a UWB monocycle pulse is thus generated. To control the power level applied to the PD, a variable optical attenuator (VOA) is connected between the three-port circulator and the PD. The generated UWB monocycle pulse is amplified by an electrical amplifier and then sent to a digital communication analyzer (DCA).

The modulation electrical signal applied to the MZM is generated by using a bit-error-rate tester (BERT, Agilent 4901B) with the fixed pattern "1000 0000 0000 0000" (one "1" every 16 bits) and a bit rate of 13.5 Gbits/s, which is equivalent to a pulse train with a repetition rate of 0.84 GHz and a duty cycle of about 1/16. The pulse shape is close to Gaussian with a FWHM of about 72 ps. The waveform of the Gaussian pulse is shown in Fig. 3(a). The erbium-doped fiber amplifier (EDFA) after the MZM is used to increase the pump power to an appropriate level. The SOA (JDS-U, CQF 872) used in the experiment has a peak small-signal gain of 26.9 dB (at 1532 nm) and a 3 dB saturation power of 10.1 dBm at a 300 mA driving current.

The physical spacing between FBG1 and FBG2 is 5 mm, which corresponds to a time-delay difference of 50 ps. Both FBGs are 2 mm long. The reflection and transmission spectra of the cascaded FBGs are shown in Fig. 3(b). The central reflection wavelengths of FBG1 and FBG2 are 1549.21 and 1552.63 nm, with 3 dB bandwidths of 0.55 and 0.87 nm. The FBG bandwidths are wide enough that no considerable distortions to the pump or probe pulses are generated. Since the pump power is usually higher than the probe power, a certain asymmetry will occur in the generated monocycle. To adjust the amplitude of the pump pulse, FBG1 is made much weaker than FBG2, with a reflectivity of about 23%, 6 dB lower than that of the FBG2 (with a reflectivity of 92%). In addition to the introduction of the time-delay difference, the two FBGs also function as an optical bandpass filter to remove the amplified spontaneous emission generated in the SOA.

In the experiment, the driving current to the SOA is set at 300 mA. The wavelength of TLS1 is tuned to 1549.01 nm, aligned with the central reflection wavelength of FBG1. The output laser power of TLS1 is adjusted to be 4.7 dBm. The bias voltage of the MZM is adjusted to be the half-wave voltage, $V_\pi = 10$ V, to maximize the extinction ratio of the pump pulse. The average optical power of the pump pulse at the input of the SOA is measured to be −7.53 dBm. The wavelength of TLS2 is set to be 1552.80 nm, aligned with the central reflection wavelength of FBG2. The output power of TLS2 is adjusted to optimize the amplitude of the probe pulse to make the generated monocycle symmetric. When the output power of TLS2 is −4.8 dBm, a monocycle that has a very good shape is obtained, as shown in Fig. 4(a).

The FWHM of the monocycle pulse is about 48 ps, which is narrower than that of the original Gaussian pulse. This is because the time-delay difference between the pump and the probe pulse is smaller than the width of the Gaussian pulse. Notice that there is

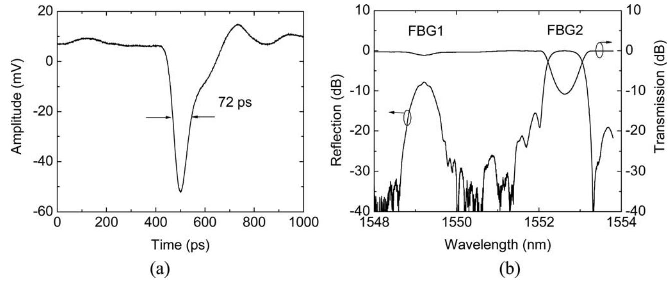

Fig. 3. (a) Electrical Gaussian pulse from the bit-error-rate tester. (b) Transmission and reflection spectra of the two cascaded FBGs.

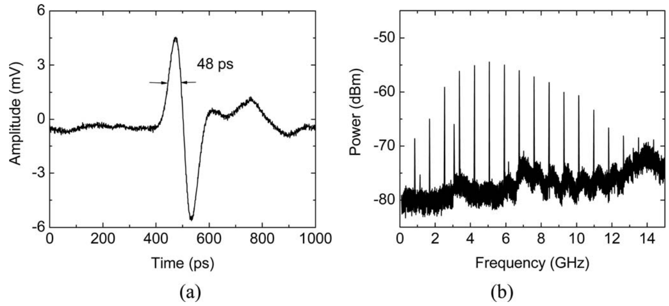

Fig. 4. Generated monocycle pulse: (a) waveform, (b) spectrum

a small peak between 700 and 800 ps in Fig. 4(a), which is also observed in Fig. 3(a); this is due to the nonideal response of the electrical amplifier after the PD. By directly sending the laser light to the optical port of digital communication analyzer DCA, this peak is made to vanish. The electrical spectrum of the monocycle pulse train, shown in Fig. 4(b), is measured by using an electrical spectrum analyzer (ESA). The frequency spacing between two neighboring lines is measured to be 0.84 GHz, which is equal to the repetition rate of the monocycle pulse train. Theoretically, the maximum repetition rate is limited by the SOA recovery time, which is usually in the range of several tens of picoseconds. Therefore the maximum repetition rate is about several gigabits per second, which is much higher than the data rate of 100–200 Mbits/s required by UWB technology.[2] The envelope of the discrete spectrum lines corresponds to the spectrum of a single monocycle pulse, which has a center frequency at about 5.0 GHz and a −10 dB bandwidth of about 9.4 GHz. This means that the generated monocycle pulse has a fractional bandwidth of 188%.

In conclusion, a novel and simple method for generating UWB monocycle pulses based on the XGM in an SOA was proposed and experimentally demonstrated. The key component in the proposed system is the SOA, in which two polarity-reversed pulses were generated thanks to the XGM. To generate a UWB monocycle, the two polarity-reversed optical pulses were reflected by two cascaded FBGs to introduce a time-delay difference. A UWB monocycle pulse with a FWHM of 48 ps and a fractional bandwidth of 188% was generated.

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