On-chip photonic generation of ultra-wideband monocycle pulses

F. Liu, T. Wang, Z. Zhang, M. Qiu and Y. Su

Proposed and experimentally demonstrated is photonic generation of ultra-wideband (UWB) monocycle pulses using a silicon microring resonator to perform phase-modulation-to-intensity-modulation conversion. The microring resonator features compact size and thus is cost-effective especially for applications in UWB communication systems that support multiple users. As a microring resonator with a *pin* diode can function as a modulator, the use of the microring resonator to realise bi-phase modulation is discussed.

Introduction: Ultra-wideband (UWB) is a promising technology for short-range high-speed wireless communications owing to its advantages in terms of low power consumption, high immunity to multipath fading, and enhanced penetration capability [1]. UWB over fibre and generation of UWB signals in the optical domain is desirable to overcome the speed bottleneck of electronic devices and the limited transmission distance of UWB communication systems [1]. Various techniques for photonic generation of UWB signals have been reported based on phase-modulation-to-intensity-modulation (PM-IM) conversion [1–4]. In some configurations, electrical Gaussian pulses are modulated onto an optical carrier using a phase modulator and the PM-IM conversion is achieved by using the dispersion of a long fibre or a fibre Bragg grating (FBG) as a frequency discriminator [2]. However, as for the application of bi-phase modulation [3], where information is encoded with the polarity of the UWB pulses, the fixed spectrum characteristics of those methods make it difficult to realise such function. Recently, a tunable Sagnac interferometer comb filter [3] and a reconfigurable asymmetric Mach-Zehnder interferometer [4] have been proposed to generate polarity switchable UWB pulses using a combination of discrete devices but the system becomes bulky and expensive. The use of miniaturised and integrated on-chip devices with electro-optic tunability is thus of much interest and could greatly reduce complexity and the cost.

In this Letter, we propose an approach to generate UWB pulses based on a silicon microring resonator. This silicon-on-insulator (SOI) based device is easy to integrate owing to its compact footprint and compatibility with electronics. In the proposed method, an electrical Gaussian pulse train is modulated onto the optical carrier using a phase modulator, and the UWB monocycle pulses are generated by using the linear resonance region of the microring resonator to perform PM-IM conversion. In addition, the UWB pulses have opposite polarities at the left and right sides of the resonance wavelength, thus it is possible to perform simultaneous bi-phase modulation of the UWB pulses by applying a *pin* diode in the microring resonator and shifting the spectrum using an electrical signal. In our experiment, UWB monocycle pulses with a central frequency of ~3.8 GHz and fractional bandwidth of ~150% are successfully generated.

Principle: The experimental setup of the proposed UWB generation system is shown in Fig. 1. The continuous-wave (CW) light is phase-modulated by the Gaussian pulses using a phase modulator. The optical field after phase modulation can be expressed as $E(t) = \exp[j\omega_0 t + \beta s(t)]$ [2], where ω_0 is the angular frequency of the optical carrier, β is the phase modulation index, and s(t) is the Gaussian pulse train with a period of T.

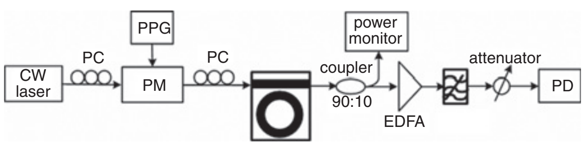

Fig. 1 *Experimental setup for generation of UWB pulses*

The basic structure of the silicon microring resonator used in the experiment is a ring evanescently coupled to a single straight waveguide. As discussed in [5], under the condition that the frequency detuning is much less than the 3 dB bandwidth of the resonator, the transfer function of the microring resonator at a certain resonance can be approximated as:

$$T(\omega) = j\tau(\omega - \omega_0) + (1/\tau_i - 1/\tau_e)/(1/\tau_i + 1/\tau_e) \qquad (1)$$

where ω_0 is the resonance frequency, $1/\tau_i$ is the power decay rate due to the intrinsic loss and $1/\tau_e$ is the power decay rate due to coupling to the waveguide. The reciprocal of the photon lifetime can be expressed as $1/\tau = 1/\tau_i + 1/\tau_e$. From (1), the spectrum of the microring resonator can offer a large linear region with opposite slope steepness factors at each side of the resonance wavelength. Therefore, the microring resonator can map the frequency detuning to the intensity change. After square-law detection using a photodiode (PD), the output of the PD a(t) is proportional to the first derivative of the Gaussian pulse as $a(t) \sim \Re P\beta\tau s'(t)$ [2], where $\Re$ is the responsivity of the PD, P is the average power at the input of the PD, τ is the photon lifetime of the microring resonator and s′(t) is the first derivative of the Gaussian pulse train s(t). Thus the monocycle UWB pulses can be generated.

Device fabrication: In the experiment, we fabricated a microring resonator with radius of ~40 μm and a ring/waveguide airgap of ~90 nm on an SOI wafer. The cross-section of the silicon waveguide is 450 × 250 nm on top of a 3 μm silica buffer layer. We use E-beam lithography followed by reactive ion etching to fabricate the device. Fig. 2*a* shows the scanning electron microscope (SEM) photo of the silicon microring resonator. The spectrum of a microring resonator is periodic with a free spectral range (FSR) of ~2.03 nm and the measured resonance at ~1552.488 nm is shown in Fig. 2*b*. The resonance has a 3 dB bandwidth of ~0.24 nm and a notch depth of ~27 dB, indicating that the resonance has a linear region spanning a bandwidth range larger than 10 GHz.

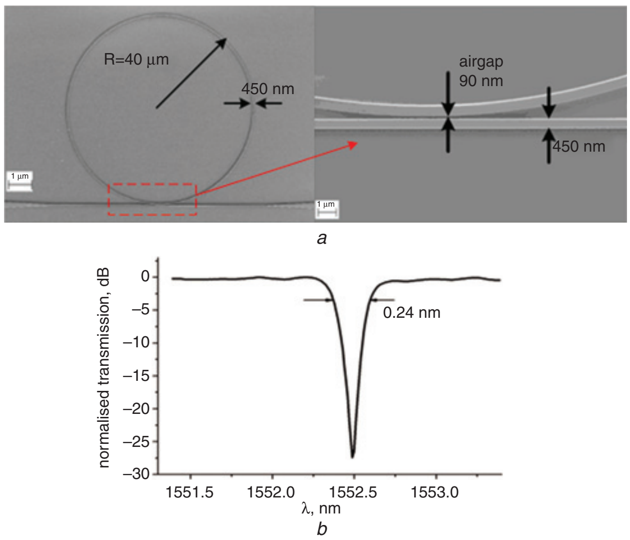

Fig. 2 *SEM photo and spectrum of microring resonator*

a SEM photo and zoom-in view of airgap
b Measured spectrum

Experiment: As shown in Fig. 1, we used a tunable laser as the CW laser source, the electrical Gaussian pulses are generated by a pulse pattern generator (PPG) operating at 10 Gbit/s with a fixed pattern of 1000 0000 0000 0000. The full width at half maximum (FWHM) of the electrical pulse is thus ~100 ps with a repetition rate of ~625 MHz. For the silicon device, we fabricated a polarisation-dependent gold grating coupler to couple light between the fibre and the silicon waveguide [5], therefore a polarisation controller (PC) is needed before the silicon microring resonator to make sure that the input light is transverse electrical (TE) mode. As the fibre-to-fibre coupling loss of the vertical coupling is ~20 dB [5], the signals are amplified using an erbium-doped fibre amplifier (EDFA) after the microring resonator. An attenuator is inserted before the photodiode to adjust the power into the PD. The tap after the microring resonator is used to monitor the output power to find the resonance wavelength.

When the wavelength of the tunable laser is 1552.608 nm, which is located near the centre of the right slope, the UWB monocycle pulses are generated at the output of the PD as shown in Fig. 3*a* with a FWHM of ~50 ps. The electrical spectrum is measured by an electrical spectrum analyser (Fig. 3*b*), where the central frequency is ~3.8 GHz and the 10 dB bandwidth is ~5.8 GHz (from 1.2 to 7 GHz), corresponding to a fractional bandwidth of ~150%. This is in accordance with the

Federal Communications Commission (FCC) regulations that the fractional bandwidth is larger than 20% or a 10 dB bandwidth is at least 500 MHz in the frequency range from 3.1 to 10.6 GHz [3]. When the wavelength of the tunable laser is tuned to the centre of the left slope at ~1552.368 nm, UWB monocycle pulses with opposite polarity are generated (Fig. 3*c*). The signal has nearly the same FWHM and electrical spectrum as those at the right slope.

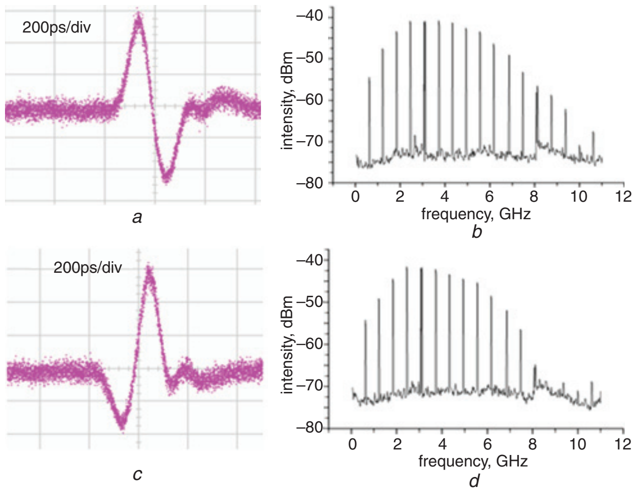

Fig. 3 *Waveforms and electrical spectra at output of PD*

a,b Waveform and electrical spectrum at right slope of resonance
c,d Waveform and electrical spectrum at left slope of resonance

Discussion: Since a microring resonator based modulator was previously demonstrated [6], it is possible to shift the spectrum of the microring resonator through carrier injection/depletion by applying a *pin* diode to the microring as shown in Fig. 4*a*. According to Fig. 4*c*, the resonance spectrum would be blue shifted with the injection of the carrier. By properly adjusting the driving voltage and the operating wavelength, the wavelength could be tuned to the centre of the left slope or the right slope of the resonance spectrum by the electrical control signal, bi-phase modulation is thus achieved. As the group delay is symmetric with respect to the resonance wavelength, there is no time shift between the pulses with opposite polarity (Fig. 4*b*). In addition, with state-of-art technology, the complete UWB generation system including the phase modulator and the PD could also be integrated on the same silicon chip [7], which will be our future work.

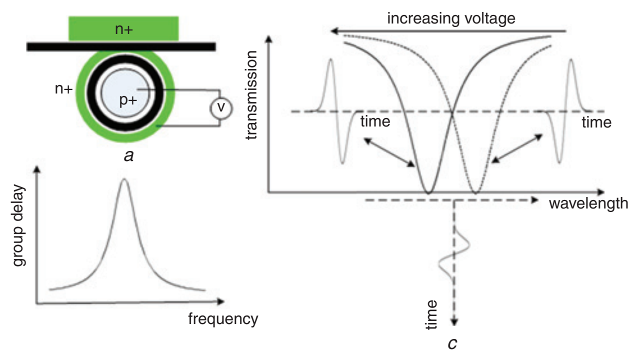

Fig. 4 *Schematic diagram of microring resonator with pin diode*

a Implementation
b Group delay curve of microring resonator
c Principle of bi-phase modulation

Conclusion: We have proposed and experimentally demonstrated generation of UWB monocycle pulses using a phase modulator and a silicon microring resonator to perform PM-IM conversion. This simple and cost-effective method is promising for practical applications in UWB communication systems.

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