Generating 20 GHz and 40 GHz Pulse Trains from a 10 GHz Mode-Locked Laser Using a Tunable Planar Lightwave Circuit and Nonlinear Wavelength Conversion

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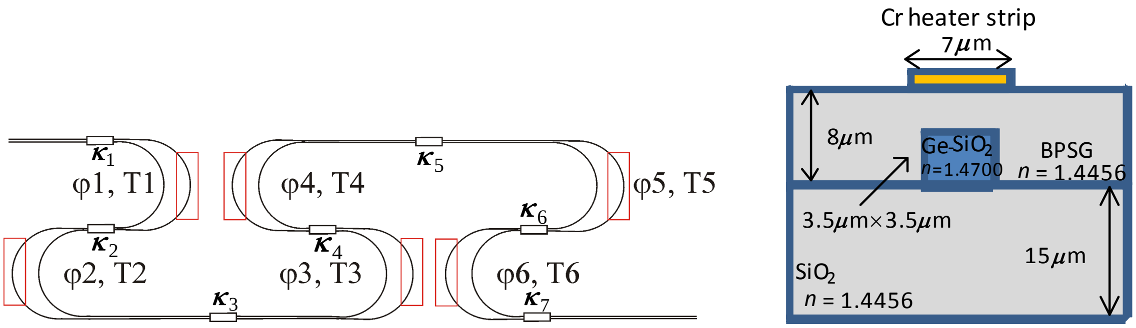
Abstract: We demonstrate the generation of 20 GHz and 40 GHz pulse trains using a tunable planar lightwave circuit (PLC) and nonlinear wavelength conversion. The PLC is a 6-stage lattice-form Mach-Zehnder interferometer fabricated in silica-on-silicon technology.

OCIS codes: (130.3120) Integrated optics devices; (060.4510) Optical communications

1. Introduction

The generation of pulse trains at different repetition rates has applications in various domains, such as optical sampling, high-speed communications, and photonic signal processing [1]. One method to generate high repetition rate pulse trains is to multiply the repetition rate of a lower rate mode-locked laser. Many different approaches exist, for example spectral filtering [2-4] and the temporal Talbot effect [5,6]; however, it is either difficult to perform tunable pulse repetition rate multiplication (PRRM) or the output is a pseudo-multiplied pulse train, i.e., the pulses are multiplied in intensity only and not in field (the output intensity appears at the higher rate but the phase and spectral relations are not maintained after multiplication and as such, the output exhibits pulse-to-pulse phase variations which are undesirable for certain applications). In this paper, we demonstrate tunable PRRM using planar lightwave circuits (PLCs) and nonlinear wavelength conversion. In particular, we generate real 20 GHz and 40 GHz pulse trains from a 10 GHz mode-locked laser using a tunable silica-based PLC.



(a) (b)

Fig. 1: (a) Schematic of the PLC device. (b) Cross-section of the waveguide: the core is Ge-doped silica and the top cladding is

2. Planar Lightwave Circuit

The PLC is a 6-stage lattice-form Mach-Zehnder interferometer (LF-MZI) filter fabricated in silica-on-silicon technology [7]. Fig. 1 shows a schematic of the device as well as the waveguide cross-section. Each stage of the LF-MZI is characterized by a multi-mode interference (MMI) coupler with a splitting ratio κ_m, a total arm length difference (ΔL), and an additional phase shift (φ_m). The couplers are designed to provide a 3 dB splitting ratio and the nominal value of ΔL is 5.1 mm, which gives a free spectral range (FSR) of ≈ 40 GHz. The additional phase shifts are controlled via thermo-optic effects (T_m) in silica by applying DC voltages to the chromium (Cr) heaters located on one arm of each MZI stage. In [7], we used this PLC to generate arbitrary 4-bit binary code patterns at 40 GHz from a 10 GHz input, i.e., the patterns repeat at 10 GHz, but the pulses in the 4-bit pattern appear at 40 GHz. Note that the output ‘1010’ and ‘1111’ patterns correspond to 2× and 4×

PRRM, respectively. As such, we can generate 20 GHz and 40 GHz output pulse trains. However, due to the amplitude and phase filtering process implemented by the PLC, the pulse trains are only pseudo-multiplied.

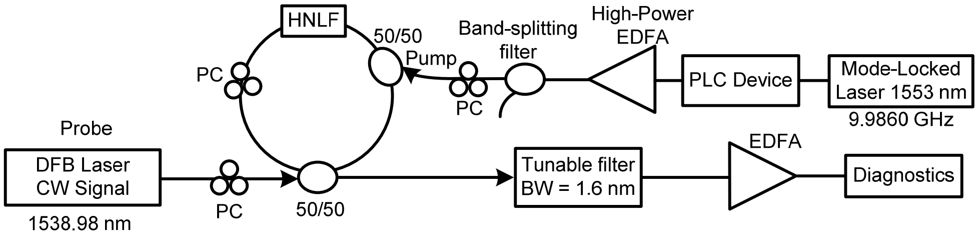
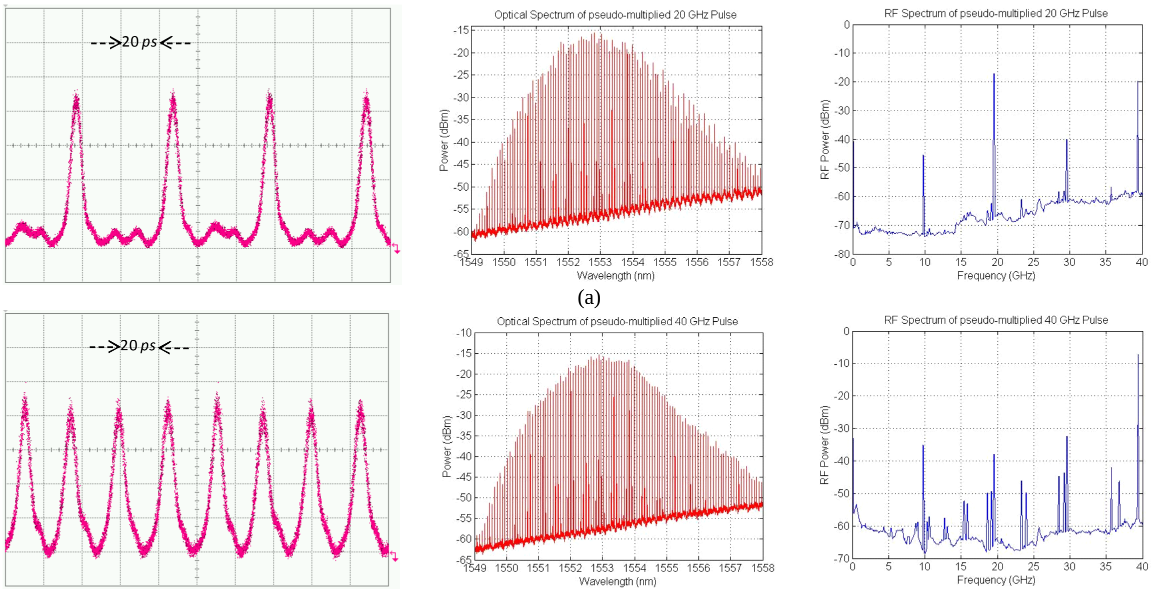


Fig. 2: Experimental setup. EDFA: Erbium-doped fiber amplifier, PC: polarization controller, HNLF: Highly non-linear fiber.

3. Experiment and Results

Fig. 2 shows the experimental setup for tunable PRRM which consists of two parts. The first part is the PLC that generates a 20 GHz or 40 GHz pseudo-multiplied pulse train. The input to the PLC is a mode-locked fiber laser at 1553 nm with a repetition rate of 9.9860 GHz. Fig. 3 shows the temporal waveforms, optical spectra, and the RF spectra of the PLC output at both 20 GHz and 40 GHz. The time measurements are made using an optical sampling module with 65 GHz bandwidth connected to a digital sampling oscilloscope; the optical spectra are measured using an optical spectrum analyzer with 0.16 pm resolution, and the electrical spectrum analyzer used for the RF measurements has a bandwidth of 40 GHz. As expected, the modes in the optical spectra for both output signals are separated by only ~ 10 GHz (in fact, the spectra look quite similar), which corresponds to the input repetition rate. This confirms the pseudo-multiplication process as 20 GHz and 40 GHz pulse trains should have (optical) modes separated by 20 GHz and 40 GHz, respectively.



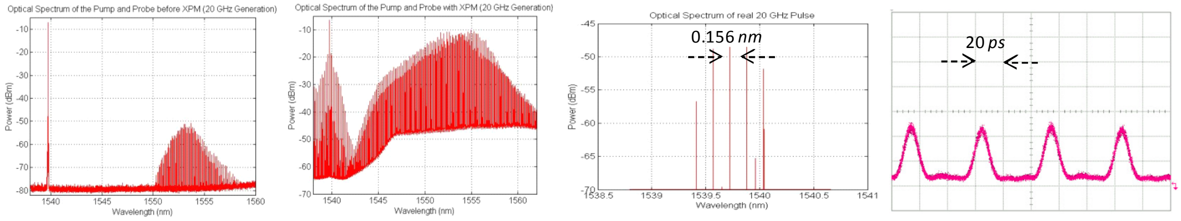
(a)

(b)

Fig. 3: Temporal waveforms, optical spectra, and RF spectra of pseudo-multiplied pulse trains at (a) 20 GHz and (b) 40 GHz.

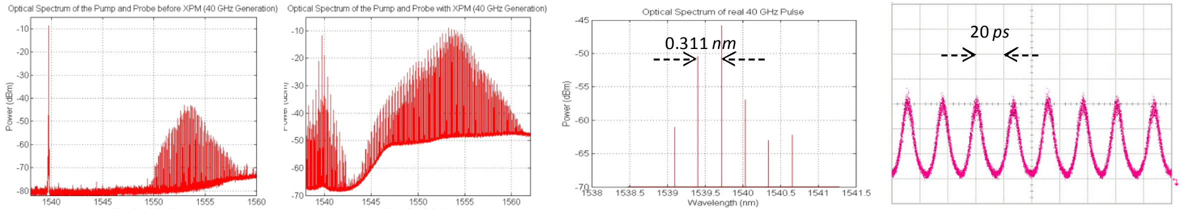
The second part is the nonlinear optical loop mirror (NOLM) that converts the pseudo-multiplied pulse train to a real 20 GHz or 40 GHz pulse train (i.e., without pulse-to-pulse phase variations) through nonlinear wavelength conversion [8]. The NOLM consists of a length of highly nonlinear fiber (HNLF), a polarization controller, and two 3 dB couplers. The HNLF has a length of 1007 m, total insertion loss of 1.86 dB, nonlinearity coefficient = 12.5 W^{-1} km^{-1}, dispersion = -0.69 ps/nm.km @ 1550 nm, and dispersion slope = 0.0074 ps/(nm^2·km) @ 1550 nm. The pump to the NOLM is the PLC output which is amplified to 22.6 dBm using a high-power erbium-doped fiber amplifier (EDFA). The probe is a CW signal from a DFB laser at 1539 nm with 10 dBm power. To reduce the noise induced by high-power EDFA, the pump and probe signals are separated using a band-splitting filter. The pump power and polarization controllers are adjusted to optimize cross-phase modulation (XPM) in the HNLF to generate a real 20 GHz or 40 GHz output pulse train at the probe wavelength at the output of the NOLM.

To measure the output pulse trains from the NOLM, we use a tunable bandpass filter with a bandwidth of 1.6 nm centered at 1539 nm. Fig. 4 (a), (b) shows the optical spectrum of the output signal from the NOLM before and after XPM for 20 GHz pulse train generation; Fig. 4 (c) shows a zoom of the optical spectrum and Fig. 4 (d) depicts the temporal waveform. Fig. 5 shows the same measurements at 40 GHz. The optical spectra reveal mode spacings of 0.156 nm and 0.311 nm, indicating conversion to real 20 GHz and 40 GHz pulse trains, respectively. The output pulse trains from the NOLM also exhibit good temporal characteristics: the RMS timing jitter for the 20 GHz and 40 GHz trains are 530 fs and 485 fs, respectively (measured using the oscilloscope and a precision time base), only slightly larger than the 390 fs and 357 fs at the output of the PLC. The output pulse widths are 10.50 ps and 10.92 ps at 20 GHz and 40 GHz, respectively, and are broader than those at the output of the PLC (7.47 ps and 8.04 ps). This may be due to walk-off in the NOLM.



(a) (b) (c) (d)

Fig. 4: Generation of 20 GHz (real) pulse trains. The optical spectrum (a) before and (b) after XPM in the NOLM, (c) zoomed optical spectrum, and (d) temporal waveform.



(a) (b) (c) (d)

Fig. 5: Generation of 40 GHz (real) pulse trains. The optical spectrum (a) before and (b) after XPM in the NOLM, (c) zoomed optical spectrum, and (d) temporal waveform.

5. Conclusion

In summary, we have demonstrated the use of a tunable PLC and nonlinear wavelength conversion to generate 20 GHz and 40 GHz pulse trains from a 10 GHz mode-locked laser. The pulse trains exhibit short output pulses, uniform amplitude, and low RMS jitter. It should also be possible to generate WDM pulse trains with tunable repetition rates by using multiple CW DFB lasers (probe signals) at the input of the NOLM.

6. References

[1] E. Ciaramella, G. Contestabile, A. D'Errico, C. Loiacono, and M. Presi, "High-power widely tunable 40-GHz pulse source for 160-Gb/s OTDM systems based on nonlinear fiber effects," IEEE Photon. Technol. Letters, vol. 16, pp. 753-755, 2004.

[2] A. M. Weiner, "Femtosecond optical pulse shaping and processing," Prog. Quantum Electron., vol. 19, pp. 161-237, 1995.

[3] P. Petropoulos, M. Ibsen, M. N. Zervas, and D. J. Richardson, "Generation of 40-GHz pulse stream by pulse multiplication with a sampled fiber Bragg grating," Opt. Lett., vol. 25, pp. 521-523, 2000.

[4] D. E. Leaird, S. Shen, A. M. Weiner, A. Sugita, S. Kamei, M. Ishii, and K. Okamoto, "Generation of high-repetition-rate WDM pulse trains from an arrayed-waveguide-grating," IEEE Photon. Technol. Lett., vol. 13, pp. 221-223, 2001.

[5] J. Azaña and M. A. Muriel, "Temporal self-imaging effects: theory and application for multiplying pulse repetition rates," IEEE J. Sel. Topics in Quantum Electron., vol. 7, pp. 728-744, 2001.

[6] D. Pudo and L. R.Chen, "Tunable passive all-optical pulse repetition rate multiplier using fiber Bragg gratings", Journal of Lightwave Technology, vol. 23, pp. 1729-1733, 2005.

[7] P. Samadi, I. A. Kostko, A. Jain, L. R. Chen, P. Dumais, and C. L. Callender, S. Jacob, and B. Xia, "Tunable 6-Stage Lattice-Form Mach-Zehnder Interferometer for Arbitrary Binary Code Generation at 40 GHz," Proc. Conf. on Opt. Fiber Commun., 22 - 26 March 2009, San Diego, CA, paper OWO6.

[8] T. Sakamoto, F. Futami, K. Kikuchi, S. Takeda, Y. Sugaya, and S. Watanabe, "All-optical wavelength conversion of 500-fs pulse trains by using a nonlinear-optical loop mirror composed of a highly nonlinear DSF," IEEE Photon. Technol. Lett., vol. 13, pp. 502-504, 2001.