Design, Fabrication and Characterization of an InP-based Tunable Integrated Optical Pulse Shaper

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A tunable integrated semiconductor optical pulse shaper is presented. The device consists of a pair of 200 GHz arrayed waveguide gratings with an array of electro-optical phase modulators in between. It has been fabricated in InP/InGaAsP material for operation at wavelengths around 1.55 μm, and has an optical bandwidth of 36 nm. Multimode inputs to the waveguide gratings are used to flatten their optical passbands, leading to a fourfold decrease in pulse ringing. The device is able to (pre-) compensate dispersion values of 0.2 ps/nm for 300 fs pulses, which is a suitable value for applications in e.g. biomedical multi-photon imaging.

Introduction

Spectral phase control of short optical pulses with wavelengths around 1550 nm has many applications. In telecommunications it can be used for dispersion (pre-) compensation in ultrafast time domain multiplexing systems [1] and arbitrary waveform generation [2], e.g. to create rectangular pulses to define switching windows. More advanced telecommunication coding technologies such as optical code-division multiple-access (O-CDMA), also make use of spectral phase control [3]. Other important applications can be found in bio-imaging, using second harmonic pulses for multiple photon excitation [4].

In this work we present a 4-THz bandwidth InP-based integrated pulse shaper, consisting of an AWG-pair and electro-optical phase modulators. Special attention is paid to the suppression of ringing of the signal due to the non-flat AWG channel transmission [5]. We have used a relatively new interferometric measurement technique and applied it for the first time to an integrated optical circuit to characterize the optical signal both in power and in phase. The pulse shaping capabilities of the pulse shaper are shown and its application as a dispersion compensator is studied.

Design and fabrication

The pulse shaper presented in this work is schematically depicted in Fig. 1(a). The first AWG is used to spectrally decompose the signal (pulse). An array of phase modulators (PHMs) is integrated to modulate the phase of these spectral components and apply an arbitrary dispersive profile. A second AWG is then used to recombine the spectral components. The transmission spectra of the two AWGs should overlap, to optimize the transmission. Separate temperature controls for both AWGs allow for individual tuning of these transmission spectra.

The AWG pair is designed to have 20 channels with a 200 GHz spacing and a center frequency around 1550 nm. The free spectral range is 4 THz, i.e. equal to 20×200 GHz. To minimize ringing, i.e. the appearance of satellite pulses at 5 ps time spacing (i.e. the inverse of 200 GHz), due to the non-flat AWG channel transmission, we have added waveguides with MMI couplers for flat-top transmission [6]. In Fig. 1 the design and realization of our 20 × 200 GHz pulse shaper is shown.

The PHMs have a length of 5 mm and are designed for TE phase shifting efficiency of 2π radians at -5 V. The epitaxial layer thicknesses and doping levels were chosen to be compatible with possible future active-passive integration [7]. The structure is etched using an optimized two-step CH_4/H_2 reactive ion etching (RIE) process, to create both high-contrast (deep) and low-contrast (shallow) waveguides (Fig. 1(c)). Polyimide is used for planarization of the surface and for passivation of the PHMs. A layer of titanium-gold (Ti/Au) is then evaporated and a pattern is etched wet chemically to create the electrical contacts to the PHMs.

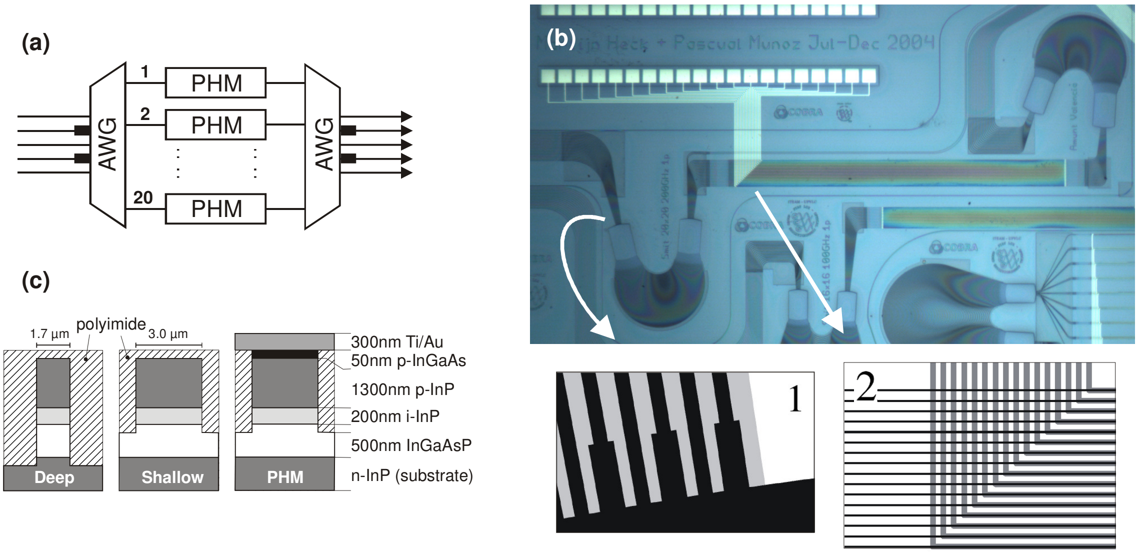

Fig. 1 (a) Schematic overview of the AWG-based pulse shaper configuration with both Gaussian and flat-top transmission in/outputs. (b) Picture of the realized device. The close-up of the mask designs show the MMI in/outputs (1) and the metal contacts to the 20 PHMs (2). (c) Schematic cross-sections of the high-contrast (Deep), low-contrast (Shallow) and phase modulating (PHM) waveguides.

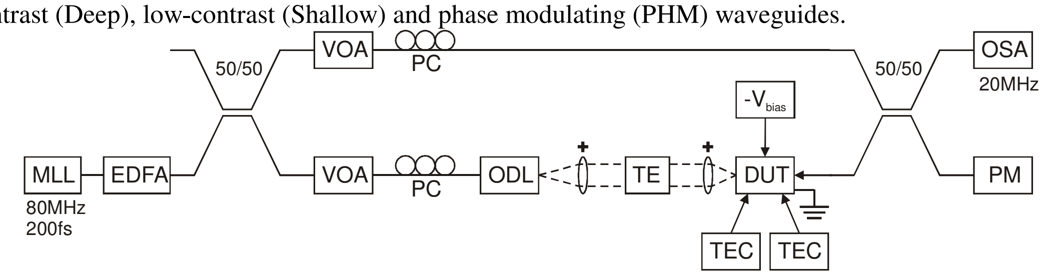

Fig. 2 Schematic overview of the SIMBA measurement setup. MLL: 80-MHz mode-locked fiber laser, EDFA: erbium-doped fiber amplifier, VOA: variable optical attenuator, PC: polarization controller, ODL: optical delay line, TE: polarization filter, TEC: thermo-electric cooler, OSA: optical spectrum analyzer, PM: power meter, DUT: device under test, 50/50: 3-dB fiber coupler. All fiber pigtailed components use dispersion shifted fiber.

Characterization

In this work we use a relatively new technique for ultrashort pulse characterization, named SIMBA (Spectral Interferometry using Minimum-phase Based Algorithm [8]), and apply it for the first time to the characterization of an integrated optical circuit. With this technique it is possible to completely characterize a short optical pulse, i.e. both the power and the phase profile. The setup used in this work is shown in Fig. 2. In this setup the 80 MHz, 0.3 ps pulses from the mode-locked fiber laser are split between the arm with the chip and a reference arm of approximately the same length. A delay line is used to delay the pulses propagating through the chip by about 100 ps with respect to the pulses in the reference arm. The interference spectrum of both pulses is then recorded with a high-resolution spectrum analyzer with a resolution of 20 MHz, recording 20.000 points per spectrum (APEX AP2041A). The delay between the pulses of 100 ps results in fringes in the interference spectrum of about 10 GHz width. Using an iterative Fourier algorithm on the spectrum, the pulse shape at the output of the chip can then be calculated [8].

In Fig. 3(a) the on-chip losses of the pulse shaper are shown. Peak transmission is at -19 dB for the Gaussian shaped passbands. The addition of MMIs at the inputs and outputs of the AWGs, as shown in Fig. 1(a) flattens the passband and increases the 3-dB bandwidth from 0.3 nm to 0.8 nm as compared to the Gaussian passband. The peak transmission is reduced by about 4 dB – 5 dB. The losses of the (shallow) waveguides are determined to be (3.8 ± 0.5) dB/cm using a Fabry-Pérot based loss measurement technique. A voltage of -6 V induces a phase shift of 2π radians in the 5-mm PHMs, with a dark current below 5 nA at this voltage. Optical losses induced by the applied field over the PHM are negligible, i.e. less than 0.1 dB per PHM when the voltage is decreased from 0 V down to -10 V.

Using the SIMBA measurement technique, the power and phase spectra of a 0.3-ps pulse train after propagation through the pulse shaper are determined (Fig. 3(b)). As can be seen the phase of the channels can be separately tuned by applying a reverse bias voltage over the respective PHMs. The phase of the spectrum is quantified at 0 V, -2 V and -4 V bias on the PHMs. Using multiple sets of measurements, the error margin achieved in the phase is less than ±0.25 radians. By optimizing the PHM settings, a pulse shape with minimized duration can be achieved, as shown in Fig. 4(a). As can be seen, severe ringing in the form of satellite pulses takes place. These satellite pulses are spaced at 5 ps, corresponding to the 200-GHz AWG channel spacing. Their peak power is between 50% and 60% of the central pulse peak power. In Fig. 4(b) it can be seen that when flat-top AWG inputs are used this ringing is significantly suppressed to about 12% to 16% of the central pulse peak power. Moreover the central pulse peak power is increased by about 25% as compared to pulse shaping using Gaussian AWGs. For both cases the pulse duration is about 0.3 ps at FWHM.

As a practical application we have investigated the possibilities for using the pulse shaper as a dispersion (pre-) compensator. The pulse peak power can be reconstructed to within 95% of the input pulse peak power for dispersion values of ±0.2 ps/nm, which is the equivalent of about 10 m of single-mode fiber. Intrachannel dispersion, i.e. within the AWG passband, is the limiting factor.

Conclusion

In this work we have presented an integrated optical pulse shaper, fabricated in the InP/InGaAsP material system and working for pulses with wavelengths around 1.55 μm. Pulse shaping was investigated for pulses at 80 MHz and with a duration of 0.3 ps. Our flat-top AWG inputs strongly reduce the pulse ringing as compared to AWGs with Gaussian inputs by a factor of four, i.e. from 50% - 60% down to 12% - 16% and are well able to reconstruct the short pulses, i.e. the output pulses also have a duration of 0.3 ps. The application of the pulse shaper as a dispersion compensator was

investigated. The pulse shaper is well suited to compensate dispersion values of up to 0.2 ps/nm, with pulse peak power reconstruction of over 95%.
The fabrication of the pulse shaper is compatible with the fabrication of integrated mode-locked lasers. This makes it possible to make a fully integrated arbitrary pulse generator for wavelengths around 1.55 μm.

This work was supported by the Netherlands Foundation of Scientific Research (NWO), the Dutch Technology Foundation STW through a Valorization Grant, by the Dutch Ministry of Economic Affairs through the NRC Photonics Grant and the "Towards Freeband Communication Impulse" technology program, and by the ePIXnet Network of Excellence.

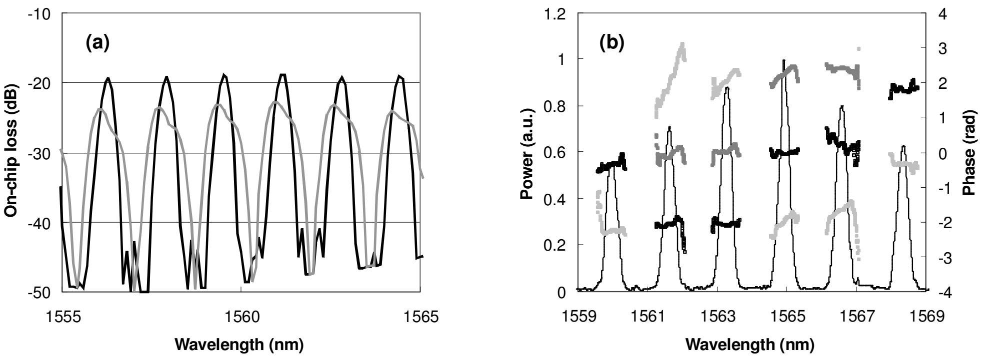

Fig. 3 (a) Comparison of the transmission (on-chip) of a pulse shaper with Gaussian AWGs (black) with flat-top AWGs (grey). The AWG temperature difference is 4 ˚C in both cases. (b) Measured phase of the spectral components of the transmitted pulse spectrum using Gaussian AWG channels. The PHMs in the channels are separately biased at -2 V (dark grey) and -4 V (light grey) and compared to the unbiased case (black). The transmitted spectrum is also shown.

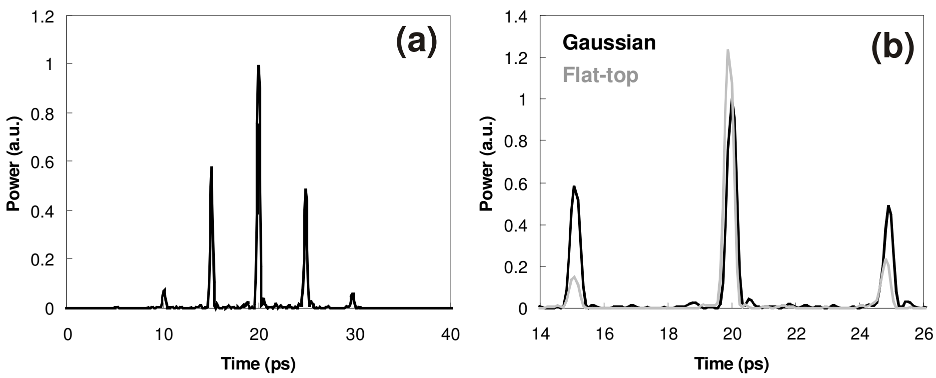

Fig. 4 (a) Pulse shape obtained using optimized PHM settings for Gaussian AWG passbands. (b) Comparison of the pulse shapes obtained with Gaussian (black) and flat-top AWG passbands (grey). Both plots are normalized to the peak power of the pulse obtained with Gaussian AWGs.

References

[1] H. Tsuda et al., IEEE Photon. Technol. Lett., vol. 11, pp. 569-571, May 1999
[2] K. Takiguchi et al., Electron. Lett., vol. 40, no. 9, pp. 537-538, 2004
[3] Chen Ji et al., IEEE J. Select. Topics Quantum Electron., vol. 11, no. 1, pp. 66-77, Jan./Feb. 2005
[4] H.C. Guo et al., 15th International Conference on Ultrafast Phenomena, paper TuE8, August 1. 2006
[5] M.J.R. Heck et al., IEEE J. Sel. Topics Quant. Electron., vol. 12, no. 2, pp. 265-276, Mar.-Apr. 2006
[6] M.J.R. Heck et al., Proc. ECIO 2005, Apr. 2005, pp. 351–354
[7] J.J.M. Binsma et al., Proc. Symp. IEEE/LEOS Benelux, 2001, Brussels, pp. 245-248
[8] A. Ozcan et al., LEOS Summer Topical Meetings, 2005 Digest of the, 25-27 July 2005, pp. 215- 216