Tunable Optical Delay Line Using Quadratic-Coupled Waveguide Lattices

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***Abstract*—A broadband variable optical delay line is proposed based on the discrete harmonic oscillation in waveguide lattices with a quadratic distribution of coupling coefficients. Theoretical analysis and numerical simulations are performed with the sample design.**

Keywords—Telecommunications devices; Microphotonics; Optical buffers; Waveguides

I. INTRODUCTION

Variable optical delay lines (ODLs), or optical buffers, are one of the basic building blocks of the rapidly developing all-optical networks. The existing techniques of ODLs are mostly realized by either increasing the propagation length (delay-line buffer, etc.) or decreasing the group velocity (slow-light buffer, etc.) [1]. The slow-light ODLs are often based on strong resonant effects and suffer from narrow bandwidth and small delay time.

Here we will present a novel idea to realize the ODL using the waveguide lattice (WL) [2]. In the WLs with a quadratic distribution of coupling coefficients (QWL), discrete harmonic oscillation (DHO) effect can happen by exciting a single waveguide [3]. In principle, the QWL-based ODL is similar to the delay-line based ODL [4], replacing the direct fiber or waveguide ODL with the QWL. By applying the DHO effect, the footprint of ODL device can be shrunk without inducing the bending loss. And the merit of broad bandwidth is also maintained as the DHO is not a resonant effect and the coupling coefficient generally exhibits a low dispersion.

II. DESIGN AND SIMULATION

The conceptual design of the proposed ODL is shown in Fig. 1. The light is coupled into one waveguide at the bottom of a WL (IO waveguide in short), and it then winds up and down periodically (sinusoidal) in the course of forward propagation (i.e., the DHO effect). Each waveguide in the WL is made identical, while the distances between the adjacent waveguides are engineered to follow a quadratic distribution of coupling coefficients [3, 5].

The light distribution along the IO waveguide would fluctuate periodically as sketched in Fig. 1(b). In each period, only a short segment of the waveguide has the optical field (the region z_s in Fig. 1b), leaving the other part idle with zero field. Consequently, smaller footprint can be achieved as the QWL-based ODL in Fig. 1(c). Two parallel high reflection (HR) mirrors are equipped to fold the propagation path of direct QWL in the horizontal direction. For the non-IO waveguides, the HR mirrors are fixed; while for the IO waveguide, the HR mirrors (called shutter mirrors hereafter) can be switched on and off, in other words, between the HR mode and the transmission mode. The operation of QWL-based ODL consists of three main stages: input, storage and output. On the input or output stage, the shutter mirrors are switched off, and an optical pulse train can be launched into or flows out of the IO waveguide. The optical pulse train may contain multiple bits of data, whose maximum volume is determined by the data rate and the temporal oscillation period [3]. Before the completion of the first oscillation period, the shutter mirrors are toggled on, and the optical pulse train is confined inside the mirror pair during the designed delay time.

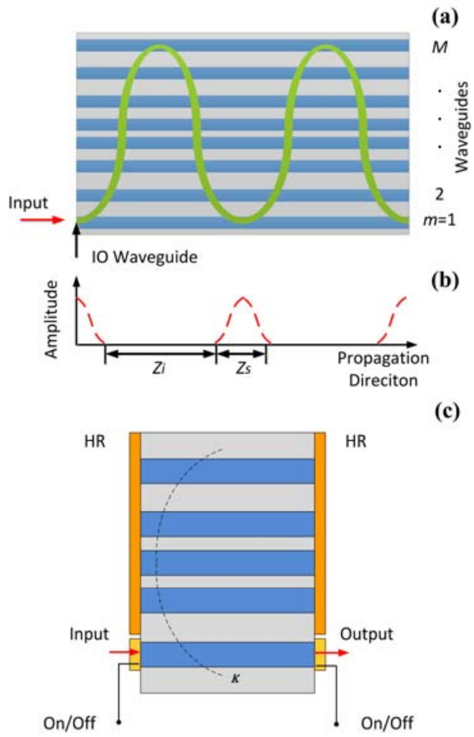

Fig. 1. (a) DHO effect in the QWL (blue regions for the cores and gray for the claddings), (b) the light amplitude distribution along IO waveguide and (c) schematic design of the QWL-based ODL are presented.

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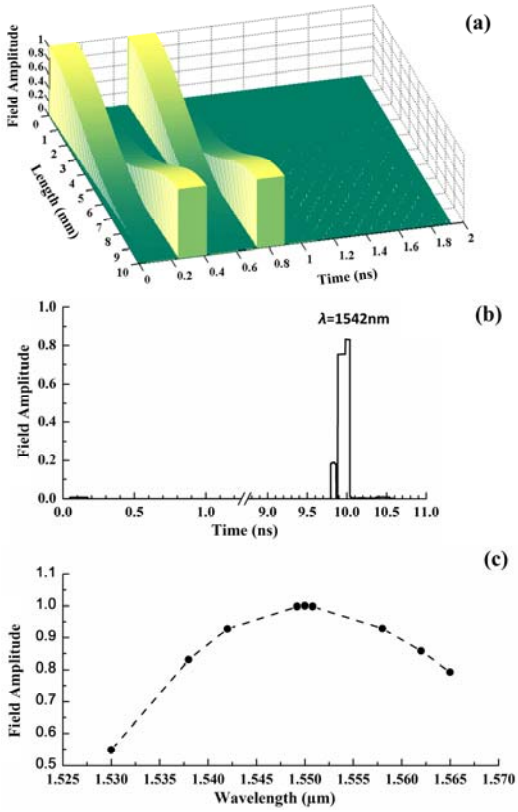

Fig. 2. The simulation results are presented. The forward-propagating field along the IO waveguide is examined, with (a) spatial-temporal distribution at 1550nm wavelength, temporal waveforms at the output end (b) at 1542 nm. The maximum field amplitudes at the output end over the whole C-band is shown in (c).

The well-developed time-domain transfer matrix method (TD-TMM) is applied in the simulations by Mathematica, based on the coupled mode theory [6, 7]. In the sample design, the materials are pure silica for the cladding regions and B_2O_3-doped silica for the core regions. The material dispersion is determined by the Sellmeier's formula. There are 25 waveguides with length 10mm and width 6μm. The effective refractive index is 1.44328 at wavelength 1550nm. The slab waveguide model is used to calculate the coupling coefficients for different refractive indices and different gap distances between the adjacent waveguides [7]. The distances between the adjacent waveguides are designed at 1550nm to meet the requirement of quadratic distribution of coupling coefficients and the oscillation spatial frequency of 0.04π mm^{-1}[3]. For the other wavelengths, the gap distances fix as those at 1550nm, and the coupling coefficients are computed accordingly.

The simulation results are presented in Fig. 2 for both the single wavelength of 1550 nm and a broad wavelength region of C-Band (1530 – 1565 nm). It can be seen that perfect pulse can be retrieved for single wavelength 1550nm, after the targeted time delay of 0.481 ns. It corresponds to the propagation length of 100 mm, though the physical length of waveguide is only 10 mm. The modulation function for the shutter mirrors is opened for full transmission from 0 to 0.173 ns, and then switched to full reflection for a duration of 0.481 ns before they are finally switched to the transmission mode again for the output of optical signals. It is noted that the input-output response is nearly 1 during the time span of 0.173 ns. Therefore, the maximum number of delayed optical pulses can be 17 bits for the data rate of 100 Gbps, or 170 bits for 1000 Gbps. However, when the dispersion effect is considered, the maximum allowed date rate is limited by the pulse distortion. For the other typical wavelength of 1542 nm, the delayed time is designed to be 20 times of the delay time resolution (0.481ns as aforementioned), or around 10 ns. The output is attenuated by a factor of about 0.75 in amplitude, or slightly above 3 dB in optical power. It is noted that there are small amount of sudden increase at about 10.0 ns. It is because some portion of energy exists in the backward-propagating field before the mirrors are toggled off. As to the small peaks that occur earlier, they are leakage resulted from the sidebands of main pulses and the variation of oscillation frequency. To investigate the dispersion over the C-band, the delay time is chosen to be 10 times of the delay time resolution (0.481 ns aforementioned), or about 5 ns. It can be seen from Fig. 2(c) that the attenuation of amplitude stays below 3 dB over the whole C-band.

III. Conclusions

In conclusions, a unique design of optical delay line is proposed by using the discrete oscillation effect in waveguide lattices. The device design can achieve a time delay up to 5ns, with the 3dB-bandwidth spans over the whole C-band and the delay time resolution of 0.5 ns. The data capacity is up to 17 bits at the data rate of 100 Gbps (or 170 bits at 1000 Gbps). The propagation path of our design is folded by up to 5 times (or 10 times for the one-port design) as compared to the conventional optical buffers using the direct fiber delay lines. The footprint of the device is 10 mm X 0.5 mm, and 20 of them can fit into the area of about $1cm^2$. This design may be useful for optical buffering and signal processing in all-optical networks and optical computing.

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