Compact Programmable Monolithically Integrated 10-Stage Multi-Channel WDM Dispersion Equalizer on Low-Loss Silicon Nitride Planar Waveguide Platform

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Abstract: We demonstrate a tunable dispersion equalizer on a low loss Si_3N_4/SiO_2 planar waveguide platform. The equalizer has a tuning range of ±550 ps/nm, a footprint of 222.5 mm^2, and can compensate multiple WDM channels simultaneously.

OCIS codes: (230.7390) Waveguides, planar; (130.3120) Integrated optics devices; (130.2035) Dispersion compensation devices

1. Introduction

Tunable optical dispersion compensators (TODC) are of great importance to optical high speed communications since dispersion tolerance is inversely proportional to bit rate square. The tunability of such devices provides a great way to dynamically compensate for residual chromatic dispersion, which can fluctuate due to temperature changes and path changes in reconfigurable optical networks as well as end of life device and system characteristics. Fiber and free space optic based compensators typically have high loss and are expensive. Today's strongest alternative is DSP-based coherent compensators that can compensate for a wide range of optical distortions such as chromatic dispersion (CD); solutions with lower price and power dissipation for short and mid-distance communication where dispersion might not be as severe are necessary. Additionally the ability to simultaneously compensate multiple WDM channels with a low loss compensator becomes attractive when dealing with WDM systems and keeping power margins low.

In this paper, we demonstrate the first fabrication of a 10-stage monolithically integrated TODC on a low-loss high aspect ratio Si_3N_4/SiO_2 planar waveguide platform. The platform has been demonstrated in [1] and has shown record low losses on integrated waveguides. The platform uses stoichiometric Si_3N_4 as the core, which provides a high index contrast between core and cladding giving the platform with great bending capabilities, while the high aspect ratio mitigates the sidewall scattering loss by decreasing the mode overlap with the sidewall. Many different devices have been demonstrates on this platform and the addition of the TODC adds to the available toolbox of: AWGs [2], high Q ring resonators [3], receivers [4], and true time delays [5]. The compensator demonstrated here can dynamically compensate WDM channels simultaneously on a 100Ghz grid with a dispersion range of +/- 550 ps/nm and a maximum waveguide propagation loss of 0.6 dB (0.05 dB/cm).

2. Device Design & Waveguide Fabrication

An integrated optical lattice filter can be designed by cascading symmetric and asymmetric MZIs. The symmetric MZIs function as a variable coupler, while the asymmetric MZIs provide the wavelength dependent delays for the dispersion compensation. If the delays are integer multiples of a unit time delay, the frequency response will therefore be periodic and can be represented by the following Fourier series:

$$T(z) = \sum_{i=1}^{n} a_i \, z^{-i} \qquad (1)$$

Where n is the number of stages, z is the complex variable represented by $\exp(j2\pi n_{eff}\Delta L/c)$, and a_i is the complex expansion coefficient of the series determined by the coupling ratio and phase of each delay. In order to obtain a desired transfer function all the couplers and phase must be tuned, which can become impractical when dealing with higher order filters.

In this paper, a generalized lattice filter approach was chosen to provide a more practical tunable filter as seen in [6]. The lattice filter was optimized for dispersion compensation and ease of bias, by having the middle delays set to 2 ΔL alternating between top and bottom arm of each stage and having all the inner tunable couplers connected together electrically for a single-knob control, as shown in Fig. 1 below. The filter has a total of 21 cascaded symmetric and asymmetric MZIs, the tuning of coupler is done via thermal tuning, and the unit delay is set to 2 mm, which corresponds to a FSR of 100 GHz for a group index of 1.5.

The device was fabricated on die size of 2.25 x 0.99 cm and a minimum bend radius of 500 µm was used in order to minimize the device footprint. The waveguide geometry is 2.8 um wide by 100 nm in thickness, which is single mode and provides the high aspect ratio geometry that minimizes the mode overlap with the sidewall roughness thus decreasing the propagation loss to the low-loss regime [1]. The waveguides were fabricated using 248 nm stepper lithography on a 100 mm Silicon substrate. The lower cladding was composed of 15 um of thermal oxide while the upper cladding was 3 µm of sputtered Silicon Dioxide. The core material is stoichiometric Silicon Nitride deposited via LPCVD. The entire structure was annealed at 1050 °C in order to minimize Hydrogen absorption. Finally, NiCr heaters were deposited via evaporation, to thermally tune the device, together with Ti/Au contacts. Fig. 2. shows the cross-section of the final waveguide structure. The complete fabrication detail follows the procedures found in [5].

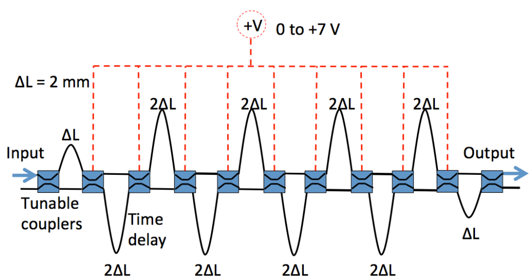

Fig. 1. Generalized lattice filter diagram with one-knob control for ease of bias. Colored boxes represent symmetric MZIs that serve the purpose of a tunable coupler.

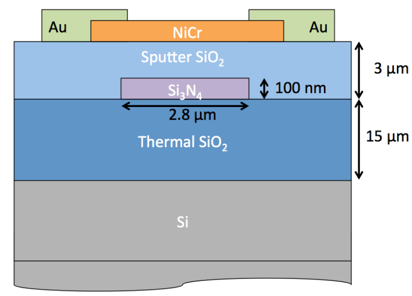

Fig. 2. Waveguide cross-section with the high aspect ratio core geometry of 2.8 um x 0.1 um.

3. Results

The waveguide propagation loss was measured using an optical frequency domain reflectometer (OFDR) from Luna Innovations via a propagation spiral test structure. The TE propagation loss is 0.05 dB/cm, which giving the maximum propagation length of 12 cm for the entire filter, the maximum propagation loss contribution to the filter loss corresponds to 0.6 dB.

The filter group delay and transmission was then measured using the same OFDR technique but with the addition of a circulator in order to measure the S_{21} parameters only. Fig. 3. and 4. display the transmission and group delay measurements, respectively. The device is measured at different bias points from 0 to 7 Volts with a maximum power dissipation of 723 mW. From Fig 4., a linear fit was performed on the group delay and a dispersion value extracted for each different bias setting. Dispersion values between +/- 550 ps/nm with group delay ripples of less than ± 6ps were measured over a bandwidth of 0.14nm. Fig. 3. also shows the transmission 3 dB bandwidth for the corresponding wavelengths.

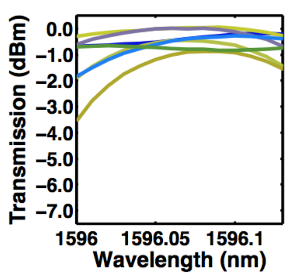

Fig. 3. Normalized filter transmission at different bias points

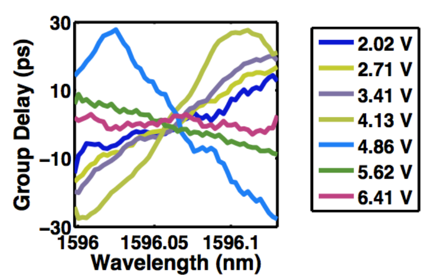

Fig. 4. Measured filter group delay at different bias points, displaying the desired linear group delay for the filter.

Each extracted dispersion value from the group delay fit can be seen in Fig. 6 plotted as a function of bias. Fig. 5. presents the filters ability to compensate dispersion on multiple WDM channels simultaneously (at least 8 channels shown in figure) with a FSR of 100 GHz. The dispersion bandwidth can be seen to decrease at higher dispersion settings, which is a direct result of the loss imbalance in each delay arm caused by the metal absorption loss. The metal absorption loss causes an increase in the total device loss that can be mitigated in subsequent runs by placing the metal heaters further away from the core.

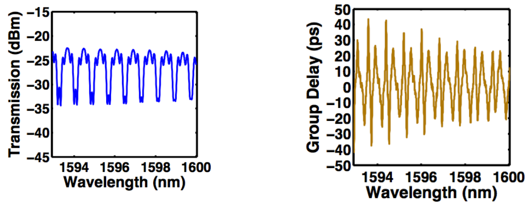

Fig. 5. Transmission (left) and group delay (right) measurement displaying a FSR of 100 GHz.

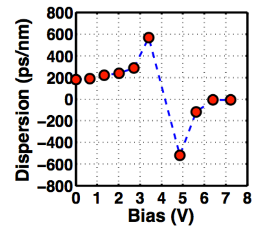

Fig. 6. Measured dispersion as a function of device bias.

Finally, transmission measurements were performed on a 40 Gbits/sec NRZ-OOK signal according to the setup in Fig. 7a. Dispersion was then compensated and Fig. 7b demonstrates the eye diagram for an uncompensated and compensated transmission over 10 Km of SMF28, respectively, showing the signal improvement achieved.

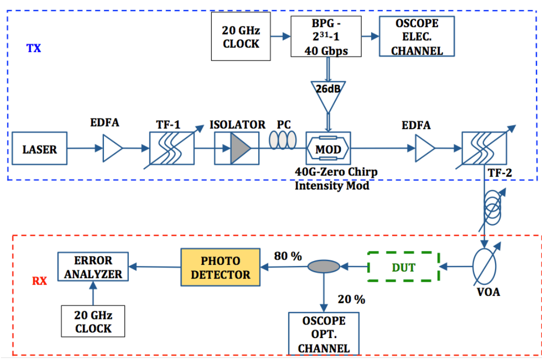

Fig. 7a. Measurement setup

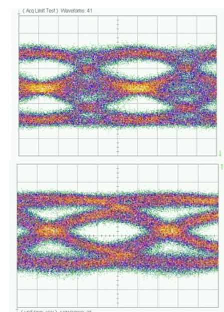

Fig. 7b. (Top) Uncompensated and (bottom) compensated eye diagram for 10 km of single mode fiber at 40 Gbits/sec NRZ-OOK transmission.

4. Conclusion

A tunable 10-stage monolithically integrated dispersion compensator was demonstrated on an integrated Si_3N_4 waveguide platform that offers superior performance to system loss due to its low waveguide propagation loss. The device can compensate for multiple channels simultaneously on a WDM grid of 100 GHz with a 0.6 dB maximum propagation loss. The platform also provides tighter bend radius, which directly corresponds with a footprint reduction of more than twice of that of its silica counterparts. The device can compensate +/- 550 ps/nm and dispersion compensation was demonstrated on a 40 Gbits/sec NRZ-OOK signal.

5. Acknowledgements

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6. References

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