Tunable Gain Tilt Compensator Using Adiabatic Mode Multiplexing

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Abstract: We built gain tilt compensator in silica on silicon using adiabatic mode multiplexer and y-branch based Mach-Zehnder interferometer. Process and design tolerant building blocks allow flexibility in achieving required response, either normally bright or tilted, and excellent optical performance.

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1 Introduction

To ensure low optical signal-to-noise ratio in a multi-stage wavelength division multiplexing (WDM) network, it is essential that all the wavelength channels have the same optical power at the receiver. Gain Tilt Compensator (GTC) compensates for the effect of stimulated Raman scattering (SRS) that causes energy transfer from the shorter wavelengths to the longer ones. SRS tilt can reach up to 4 dB over the C-Band, 191.5THz - 196.2 THz. We focus here on monolithically integrated GTC solutions in silica on silicon that offer cheap mass production and good reliability.

An early implementation of GTC consists of one delay line and two tunable couplers in the form of $3dB$ directional coupler based MZIs [1]. The phase shift ϕ of the symmetric MZI determines the effective power coupling ratio of the tunable coupler. In the power-off state, $\phi = 0$, the cross-port frequency response of the GTC is flat - it is normally bright. To get a finite tilt heat has to be applied to MZI arm. The heat induces birefringence through thermal stress giving rise to Polarization Dependent Loss (PDL). Normally tilted GTC is less susceptible to thermal stress because for power-on state its transmissivity is high and flat over the C-band. To get normally tilted device one uses more complex designs, for example a double stage architecture with two delay lines and three directional couplers [2]. A common denominator of the previous work on GTC is the use of directional couplers, a phase sensitive building block that requires precise control over waveguide fabrication process.

We show here that both normally bright and normally tilted GTC can be constructed using only process tolerant building blocks - adiabatic mode multiplexer and demultiplexer (AMM and AMDM) [3] that give access to the even and the odd modes and y-branch based MZI with optimized PDL [4] that serves as a tunable coupler in the space of these two modes. Furthermore with these building blocks we achieve greater flexibility in filter design than that provided by the usual directional coupler and delay based architectures. Choosing appropriate phase delays between two modes we are able to get transmissivity with any modulation depth for power-off state.

2 Normally bright GTC

We show the schematic diagram of the normally bright GTC in Fig. 1a. Two y-branch based MZI are connected to the double mode waveguides so they act as tunable couplers in the two-mode space. In this space the MZI transfer matrix is

$$T_{MZI}(\phi) = \begin{pmatrix} \cos\frac{\phi}{2} & i\sin\frac{\phi}{2} \\ i\sin\frac{\phi}{2} & \cos\frac{\phi}{2} \end{pmatrix}. \quad (1)$$

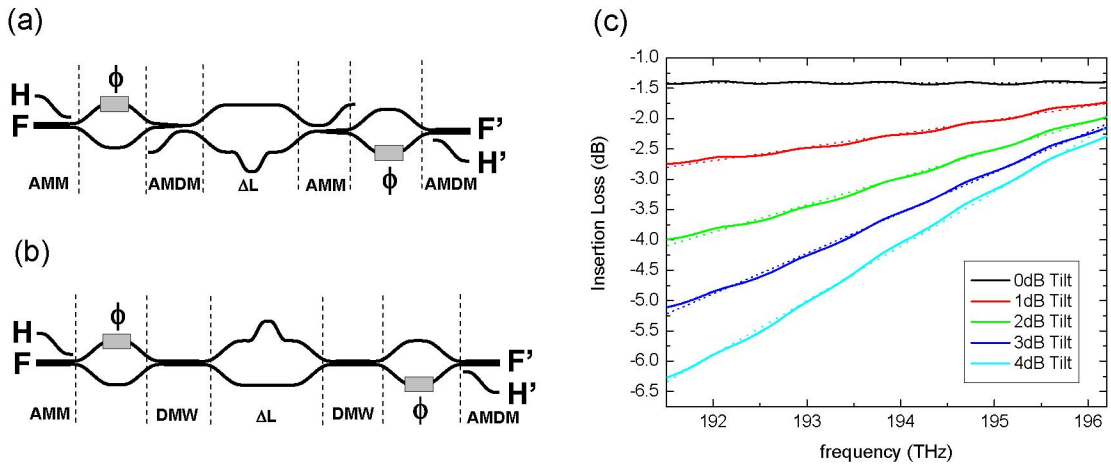

Fig. 1. (a) Schematics of the normally bright GTC. (b) Schematics of the normally tilted GTC. (c) Typical insertion loss for a delay optimized GTC. Solid line is the measurement result, dotted line is its linear fit.

When the phase $\phi = \pi/2$ MZI operates as a mode converter: it transforms the even mode into the odd one and vice versa. After the first MZI coupler produces even and odd mode combination, AMDM separates the two modes into two different single-mode waveguides. These waveguides have a delay ΔL. Then AMM combines modes from two waveguides into a single double-mode waveguide - one as an even mode and another as an odd mode. For this AMDM-delay-AMM structure we can also write a transfer matrix in modal space:

$$T_{delay}(\phi) = \begin{pmatrix} 0 & e^{-ikn_e\Delta L/2} \\ -e^{ikn_e\Delta L/2} & 0 \end{pmatrix}, \tag{2}$$

here k is the wavevector and n_e is the even mode effective index. The total transfer matrix is given by the product: $T_{GTC} = T_{MZI}(\phi)T_{delay}(\phi)T_{MZI}(\phi)$. Using Eq. (1) and Eq. (2) we calculate the transmissivity when the input is even mode and the output is odd mode:

$$T(\phi) = 1 - \sin^2\phi\cos^2\frac{kn_e\Delta L}{2}. \tag{3}$$

The last AMDM allows to pull the odd mode into output port H'. Clearly Eq. (3) describes a normally bright device. We could have induced the delay between the two modes using also a simple length L double-mode waveguide. The GTC transmissivity would be identical to Eq. (3) with one exception: $kn_e\Delta L$ would be replaced by $k(n_e - n_o)L$, where n_o is the odd mode effective index.

An important GTC parameter is its slope linearity deviation (SLD) defined as the difference between the measured GTC transmissivity and its linear fit. To minimize SLD one needs to correctly determine the delay. The delay has to be such that for the $4dB$ tilt the least curvature part of the Eq. (3) sinusoid would fit into the C-band. In our case the delay was close to $12\mu m$ and we consistently get less than 0.2dB SLD. We show attenuation curves of a typical normally bright GTC in Fig. 1c. The most challenging optical parameter is PDL which we show for three GTC modules in Fig. 2a. As expected the red edge PDL is high getting close to $1dB$ for larger tilt values.

We fabricated our devices in standard silica on silicon with 0.75% index contrast and a square 6x6μm core. The optical chip dimensions are 10x50mm^2. We placed heaters on every arm of each MZI to perform fine tuning of the delay and to set the necessary coupling ratio to achieve the desired tilt. To connect these chips to the outer world, they were fiber-chip coupled to standard single mode fibers, wire bonded and packaged in a housing of 70x20x10mm^3.

3 Normally tilted GTC

We show the schematic diagram of the normally tilted GTC in Fig. 1b. It has three y-branch based MZI - two tunable couplers and a delay. Coupler and delay MZI are connected with the double-mode waveguide

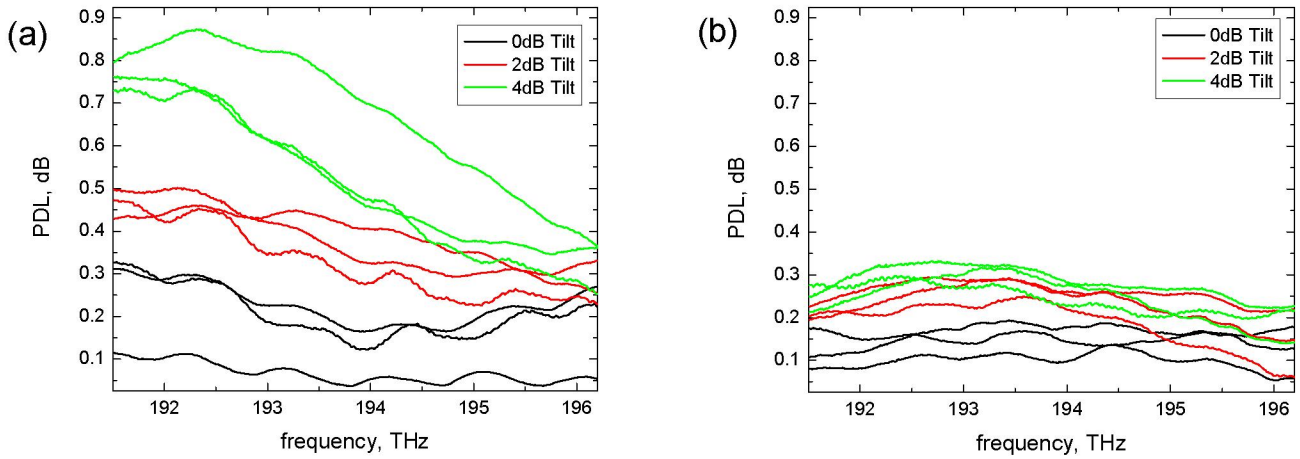

Fig. 2. PDL of three GTC modules for several tilt values: (a) Normally bright. (b) Normally tilted.

(DMW) whose length is chosen so as to induce a relative phase shift $\pi/2$ between the even and the odd mode. DMW transfer matrix is:

$$T_{DMW}(\phi) = \begin{pmatrix} e^{i\pi/4} & 0 \\ 0 & e^{-i\pi/4} \end{pmatrix}. \tag{4}$$

The total transfer matrix is: $T_{GTC} = T_{MZI}(\phi)T_{DMW}T_{MZI}(kn_e\Delta L)T_{DMW}T_{MZI}(\phi)$. Using Eq. (1) and (4) we compute the transmissivity when both the input and the output is even mode:

$$T(\phi) = 1 - \cos^2\phi \sin^2\frac{kn_e\Delta L}{2}. \tag{5}$$

From Eq. (5) it follows that when power is off, $\phi = 0$, the transmissivity is a sinusoid with maximal modulation depth and when the phase $\phi = \pi/2$ the transmissivity is flat and equal to unity.

We show the PDL measurement results for three normally tilted GTC modules in Fig. 2b. Clearly there is big improvement over normally bright case with PDL below $0.35dB$. The attenuation curves and SLD of the normally tilted GTC is the same as in normally bright one because we are using identical delay values.

4 Conclusions

We designed normally bright and normally tilted GTC using building blocks that allow the felxibility of working with both fundamental and excited mode of the waveguide. We saw that normally dark device has a superior PDL due to in part lower thermal stress. There is also another reason why normally tilted device is better. In the normally bright GTC, AMM and AMDM are both part of an asymmetric MZI so it is important that the phase accumulated by the modes travelling in the multiplexer and demupltiplexer be identical. This requirement introduces additional process sensitivity. On the other hand in the normally tilted device AMM and AMDM just put the odd mode on or pull it off the DMW and are completely phase insensitive.

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