Silicon Chirped Spiral TM Multimode Waveguide Grating

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***Abstract*—A chirped spiral TM multimode waveguide grating (MWG) is proposed that provides a considerable bandwidth exceeding 30 nm and dispersion of 25 ps/nm. The compact 30-mm-long device has a footprint of merely 0.6×0.46 mm^2.**

Keywords—silicon, multimode waveguide grating, TM mode, dispersion management

I. INTRODUCTION

In the past few decades, there has been a surge of interest in developing on-chip devices that can enable optical true time delay and dispersion management. Such devices have found broad applications in optical communication and microwave photonics. For instance, compensating for the accumulated wavelength-dependent delay and phase deviation can reduce the distortion generated during long-haul propagation [1]. Moreover, managing the time delay spectrum using dispersion controllers is critical for generating arbitrary waveforms in microwave systems [2]. By managing delay at different wavelength channels, it is possible to realize phased array antennas with different direction angles [3]. While chirped Bragg gratings have been widely used for dispersion management [4], the use of on-chip single-mode gratings is limited by the problematic separation between input and output signals, and the integration of an optical circulator is challenging. To overcome these limitations, highly efficient MWGs have been proposed to drop reflected signals [5, 6]. Additionally, TM-type devices offer several advantages such as lower propagation loss [7], evanescent fields on the upper surface [8], and lower coupling coefficients [9]. In particular, there is a desire to realize on-chip TM-type large group delay with wide bandwidth, especially for long-haul dispersion compensation and wide-range beamforming.

In this paper, we introduce a novel silicon chirped spiral MWG that incorporates a TM-type grating to reduce propagation loss and enhance fabrication tolerance [7]. This design offers an effective solution for devices that require dispersion management while performing better with TM mode. Our experimental results demonstrate that the fabricated spiral MWG exhibits a substantial maximal group delay of 812 ps and 25 ps/nm dispersion over a wide bandwidth of 30 nm. Furthermore, the device has a small chip footprint, measuring only 0.6×0.46 mm^2.

II. STRUCTURE AND DESIGN

The proposed chirped spiral MWG utilizing TM-type grating is depicted in Figure 1(a), where the light injected as TM_0 mode via the TM-type grating coupler. The light propagates through a mode (de)multiplexer and is reflected as TM_1 mode at a wavelength-dependent location within the chirped MWG. Figure 1(b) illustrates the asymmetric grating corrugations that enable the mode transformation, which is based on coupled mode theory [10]. The reflected TM_1 mode is then separated and dropped back to TM_0 mode by the mode (de)multiplexer. By linearly increasing the MWG width w, the input light is reflected with wavelength-dependent delay, according to the Bragg condition $(n_{effTM0}+n_{effTM1})\Lambda=\lambda$.

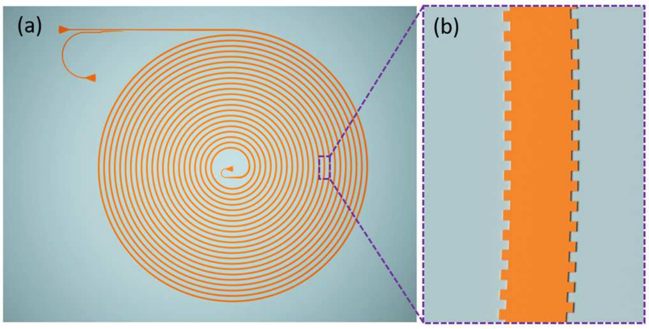

Fig. 1. Schematic configurations. (a) Top view of the whole chirped spiral TM MWG; (b) Zoom-in view of the MWG corrugations.

The utilization of TM-type MWG not only lowers the propagation loss but also improves fabrication tolerance, owing to smaller coupling coefficients compared to TE mode. To assess the propagation loss at different waveguide widths for fundamental and first-order modes of both TE and TM modes, we employed the three-dimensional volume current method [11]. Assuming that the propagation loss mainly arises from sidewall roughness, Fig. 2 illustrates a comparison of the calculated average propagation loss. When the multimode waveguide widths are less than 2 μm, the average loss of TM mode is lower than that of TE mode. However, the waveguide width cannot be too wide, as it can lead to light scattering and effective index deviation due to spiral bending. Therefore, we chose an MWG width of 1.5 μm to reduce the propagation loss while ensuring sufficient light confinement at internal bending, with a calculated propagation loss of 0.79 dB/cm. The width variation Δw = 500 nm provides a wide bandwidth and a large group delay, with the width varying from $w-\Delta w/2$ to $w+\Delta w/2$. Based on these considerations, the grating period is calculated as Λ= 402 nm.

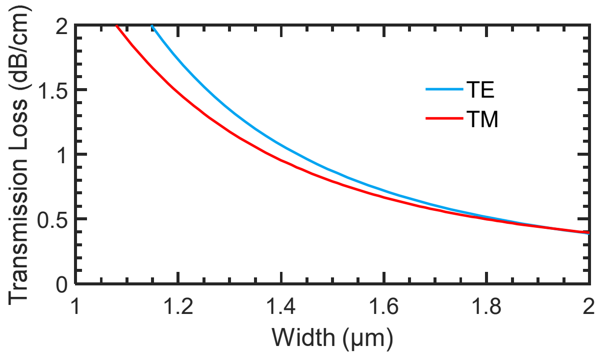

Fig. 2. Simulated avarage propagation loss at different multimode waveguide widths for TE and TM mode.

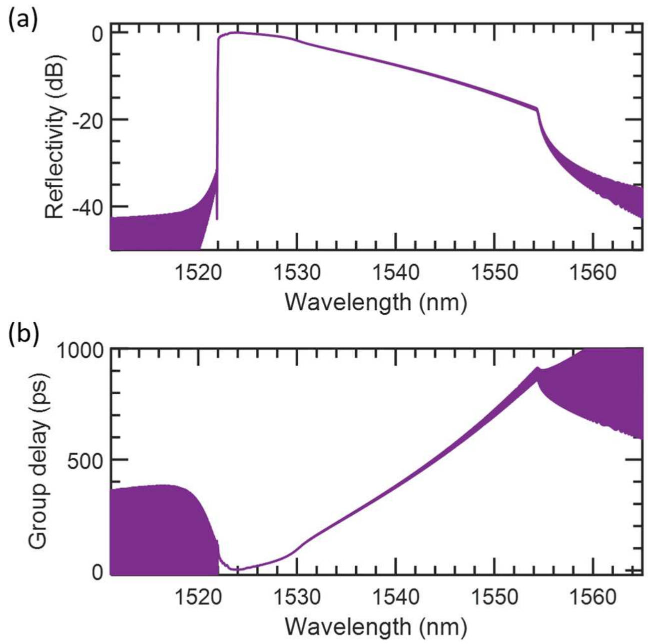

Fig. 3. Simulated (a) reflectivity and (b) group delay spectrum of the chirped spiral TM MWG.

The efficiency of calculating device performance can be improved by utilizing the transfer matrix method (TMM) [12]. In this paper, TMM is employed to simulate the reflectivity and group delay of the proposed chirped spiral MWG, as illustrated in Figures 3(a) and 3(b). To achieve a large maximal group delay, we have chosen a total MWG length of L=30 mm. Based on the fabrication samples, we set the propagation loss to 2.7 dB/cm. It should be noted that the longer wavelength exhibits higher loss as it is reflected at the rear section of the MWG, which corresponds to a longer propagation length. As depicted in Figure 3(b), the proposed MWG yields a maximal group delay of 883 ps and a dispersion of 27.17 ps/nm within a 32.5 nm 3-dB bandwidth. To mitigate the group delay ripples (GDRs) caused by asymmetric Fabry-Perot cavities, the front section of the MWG is apodized. This is achieved by smoothly transferring the straight waveguide to grating corrugations.

III. Fabrication and Results

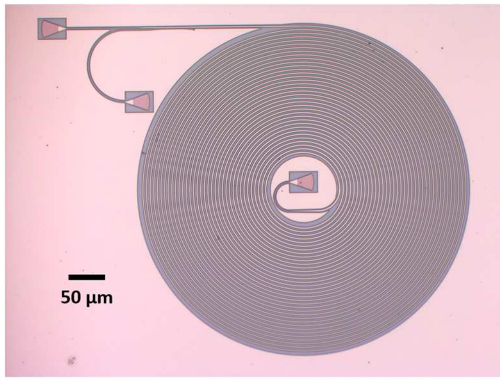

Fig. 4. Microscope image of the fabricated 30-mm-long spiral chirped TM MWG.

Following the previous design, the MWG was then fabricated with an E-beam lithography process. The top-silicon and buried-oxide layers are 220 nm thick and 2.3 μm thick, respectively. Figure 4 depicts the microscope image of the fabricated chirped spiral TM MWG. Remarkably, the 30-mm-long grating has a small footprint of only 0.6×0.46 mm^2.

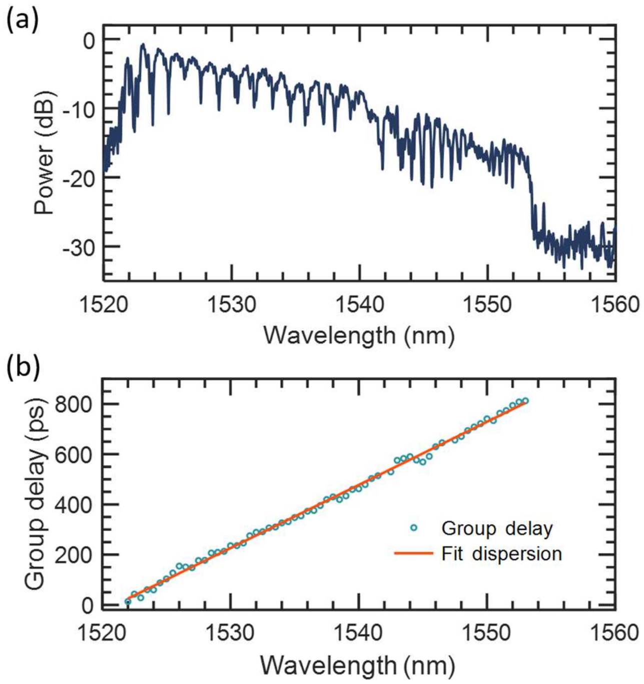

Fig. 5. Measured (a) reflectivity and (b) group delay of the chirped spiral TM MWG.

The measured reflectivity and group delay spectrum of the fabricated chirped spiral TM MWG are presented in Figure 5. Figure 5(a) illustrates that the reflection 3-dB bandwidth spans 30.3 nm, ranging from 1522.9 nm to 1553.2 nm. However, there are several defects in the reflected band due to malposed polygons in the E-beam lithography process. It is important to note that the transmission loss is 2.71 dB/cm, which is still limited by the current fabrication technology. Figure 5(b) showcases the measured group delay spectrum, with a maximal group delay of 812 ps. Consequently, the dispersion is calculated to be 25.1 ps/nm.

IV. CONCLUSION

To summarize, we have introduced and demonstrated a novel chirped spiral MWG with a 3-dB bandwidth of over 30 nm and a maximal group delay exceeding 800 ps, yielding a large dispersion of 25 ps/nm. Notably, our proposed MWG does not require a circulator and can be conveniently integrated with other on-chip devices. Additionally, the TM-type grating employed in our design minimizes propagation loss and enhances fabrication tolerance. Our presented device offers a reliable solution for on-chip large dispersion management for microwave photonics and optical communications. It is especially beneficial for devices that exhibit superior TM mode performance. In conclusion, our proposed chirped spiral MWG is a promising candidate for future on-chip applications in the field of optical communications and integrated photonics.

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