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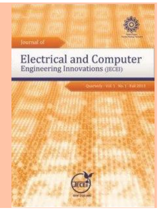
Journal of Electrical and Computer Engineering Innovations

JECEI, Vol. 5, No. 1, 2017

Regular Paper



Optical Pulse Compression Based on Nonlinear Silicon Waveguides and Chirped Bragg Gratings

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ARTICLE INFO

ARTICLE HISTORY:
Received 11 June 2017
Accepted 04 July 2017

KEYWORDS:
Optical pulse compression
Kerr nonlinearity
Molybdenum disulfide
Chirped Bragg gratings

ABSTRACT

Due to the growing demand for higher bandwidth, employing optical devices instead of electronic devices in data transmission systems has attracted much attention in recent years. Optical switches, modulators and wavelength converters are a few examples of the required optical devices. CMOS compatible fabrication of these devices, leads to much more growing of this technology. Optical pulse compression, is required for generating ultra-short pulses for high bandwidth optical transmission systems. In this work, we present a CMOS fabrication process compatible, integrated optical pulse compressor. A Silicon waveguide coated by MoS_2 for nonlinearity enhancement is used for self-phase modulation and a chirped Bragg grating utilizing corrugated silicon waveguides is employed to achieve the required anomalous dispersion. Low power and high compression ratio were considered in this work. We achieved a compression ratio of 3.5 by using a relatively low power optical pulse of 8W and a short waveguide length of 1mm.

1. Introduction

Optical time domain multiplexing (OTDM) is a widely utilized technique to increase the capacity of optical transmission systems [1], [2]. In this technique, the time domain is divided into recurrent time slots and optical pulses are repeatedly transmitted in their allocated time slots. To further increase in the capacity, the time slots must be as narrow as possible and as a result, ultra-short optical pulses are a crucial need for a high bit rate optical transmission system based on OTDM. Moreover, ultra-short pulses have other applications such as optical tomography and spectroscopy [3]. One way to create such short pulses is through the compression of longer duration pulses from a laser source [4].

The basic approach for optical pulse compression is through combining self-phase-modulation (SPM) and dispersion in a precisely controlled manner. SPM induces a nonlinear, intensity dependent phase shift to the pulse as a result of the third order Kerr nonlinearity (χ^3) in the host medium. This process generates new frequencies in the pulse spectrum as the instantaneous frequency is the time derivation of the phase. Such a pulse with altered spectrum can be compressed in time domain once an enough anomalous dispersion is applied to that. Such a time domain compression was previously demonstrated in optical fibers [4] and photonic crystal fibers based on fused silica [5]. However, due to the weak Kerr coefficient of Silica and also weak confinement of light in optical fibers, very high powers are required to induce the necessary nonlinear phase shift which limits their application. On the other hand, such fiber based structures are bulky and may not be compatible with the compact state of the art optical signal processing systems.

Silicon photonics is a promising candidate for the demonstration of various optical devices [6]. The large refractive index difference between Si and SiO_2 enables tight light confinement in silicon strip or slot waveguides in dimensions below several hundred nanometers as well as strong bends with negligible loss. On the other hand, silicon has a higher χ^3 than the silica making this material very attractive to realize devices based on Kerr effect such as pulse compressor described above. However, two components are crucial for an optical pulse compressor which are SPM and anomalous dispersion providing segments. While a simple strip silicon waveguide can be employed to induce nonlinear phase shift, designing the anomalous dispersion providing part is much more challenging. It is demonstrated that chirped Bragg gratings can provide the sufficient anomalous dispersion both in optical fibers [7] and in silicon integrated devices [8], [9] and the first optical pulse compressor chip based on silicon photonics was introduced in 2010 [10] and later in 2012 [11];

Although optical pulse compressor proposed in [10] was a great breakthrough, however, due to the relatively weak χ^3 of silicon, the length of the SPM providing waveguide is approximately 6mm which is more than to be acceptable for an integrated device. It is demonstrated that by employing Molybdenum disulfide (MoS_2) layers on top of the Si waveguide, the Kerr nonlinearity cab be increased by about 2 orders of magnitude [12] and this may lead to drastic length and optical power reduction of the pulse compressor. In this article, we propose a pulse compressor by utilizing strip silicon waveguides along with layers of MoS_2 as the top cladding layer. We show that by this modification, the length of the device can be significantly reduced to about 1mm for the SPM providing segment. The optical input power can also be reduced as a result of the increased nonlinearity. At the next section, we propose the device design and the simulation procedure.

2. Device Design

The schematic illustration of the structure is proposed in Fig. 1. The thickness of the MoS_2 layer is assumed to be 10nm typical for CVD growth of this layer [12] with a refractive index of n=4.5 at l=1550nm.

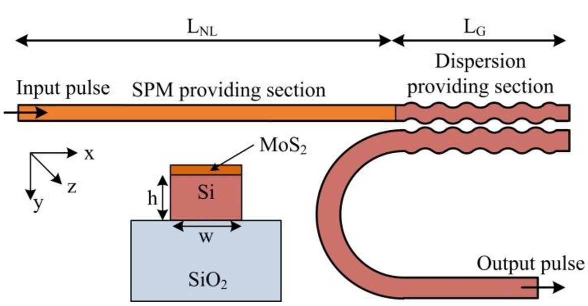


Figure 1: Top view of the proposed pulse compressor along with the device cross section.

As can be seen from Fig. 1, the pulse compressor is composed of two distinct sections. The first section provides the necessary spectral broadening through SPM with a length of L_{NL} and the second section that consists a chirped Bragg grating with a length of L_G, provides the negative dispersion to compensate the nonlinear phase generated in the first section. MoS_2 layer is only covering the first section and due to the fact that L_G is smaller than L_{NL} and also the absence of MOS_2 at the grating section, the nonlinearity imposed by the dispersion section is negligible. The height of the waveguides are 250nm, whereas the width of the input and output waveguides are 500 and 400nm, respectively. Theoretically, the nonlinear phase shift generated by SPM as the pulse propagates through the silicon waveguide results in the red and blue shifts of the leading and trailing edges of the pulse, respectively. Hence, a grating with negative dispersion is required to delay the leading edge and accelerate the trailing edge and compress the pulse. In this paper, the design and analysis is divided into three subsections. In the first subsection, the nonlinear Si-MoS_2 waveguide with the minimum length and maximum spectral broadening is designed and in the second subsection, control of the dispersion by the grating is discussed. Finally, we combine these results and investigate the pulse compression characteristics at the third subsection.

As the total device length is in the millimeter range, 3D Finite Difference Time Domain (3D-FDTD) is extremely time consuming. To analyze the structure, we employ 2D-FDTD method. To do so, we simulate the device along x and y directions as depicted in Fig. 1. We apply the effective refractive indices of the Si slab waveguide with a thickness of 250nm (along the z direction) as the materials refractive index for the 2D simulations as described elsewhere [10].

3. Results and Discussion

In this section, we design a compact highly efficient optical pulse compressor. At the first subsection, we investigate the functioning of MoS_2 coated Si waveguide as the nonlinear self-phase modulator and subsequently at the second subsection, we analyze the chirped Bragg grating and its dispersion properties.

A. Nonlinear Si-MoS_2 waveguide design

Our goal in this subsection is to achieve a considerable spectral broadening induced by SPM with the minimum possible input power or device length. To this end, we employed MoS_2 coated silicon waveguide presented recently. It is shown that χ^3 is almost two orders of magnitude larger is MoS_2 coated silicon waveguide than the Si itself. Specifically, χ^3 equals $7x10^{-18}m^2/w$ for silicon [13], whereas this value is about $1.1x10^{-16}m^2/w$ for MoS_2 coated Si waveguide [12]. The dimensions of the waveguide are 3mm, 500 and 250nm for the length, width and height, respectively. In this structure, due to the very small mode effective area of 0.15μm^2, the light confinement and subsequently, SPM induced nonlinearity increases. The spectrum of an optical pulse after propagating in MoS_2 coated Si waveguide is illustrated in Fig. 2. The input optical power is approximately 8W for this simulation. It can be shown that spectral broadening for this case almost equals that of a 6mm Si waveguide without MoS_2 coating with much higher input optical power.

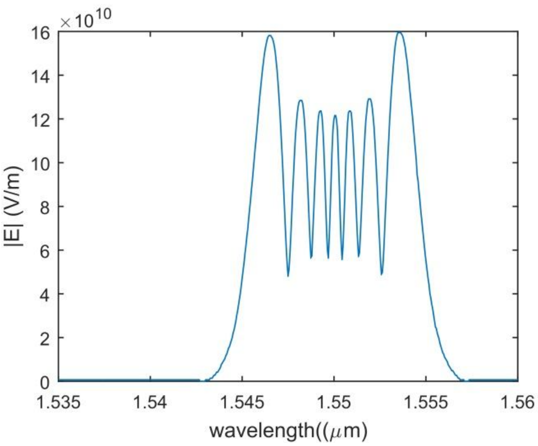


Figure 2: Spectral broadening of the input pulse for MoS_2 coated Si waveguide with a length of 3mm.

B. Chirped Bragg grating design

As stated above, the second crucial segment of the pulse compressor is a dispersive element to compensate the nonlinear phase generated at the first segment. Chirped Bragg grating can fulfill this task. The Bragg grating is composed of two waveguides (widths of w_1 and w_2) with corrugated sidewalls as shown in Fig. 1. The corrugations can be sinusoidal or square. In this article, we assumed sinusoidal corrugations. The first stage in designing the Bragg grating is to satisfy the Bragg condition as (1). In (1), β_1 and β_2 are the mode propagation constant of the first and second waveguide respectively. Take note that β_1 and β_2 correspond to a forward and backward propagating modes respectively, i.e. β_1 is positive, however, β_2 is a negative value. $\Delta\beta$ is the mismatch parameter. For the two modes to couple successfully, $\Delta\beta$ must be zero. Λ_0 is the average grating period. Coupled mode theory can be utilized to derive (1).

$$\Delta\beta(\lambda) = \beta_1(\lambda) - \beta_2(\lambda) - 2\pi/\Lambda_0 \quad (1)$$

The second stage is to determine the gap between the two waveguide sidewalls, the modulation depth and also the grating length. These factors are important as they have a great impact on the coupling efficiency and the bandwidth of the coupling. One extremely important point must be emphasized here. As the sidewalls of the waveguides are corrugated, the input waveguide acts like a grating by itself and reflects the input light. To avoid reflection of the light at 1550nm, we have to choose the waveguide widths to be different. In our final design, the width of the input and output waveguides are 500 and 400nm, respectively and the grating period is set to 318nm to phase match two modes at 1550nm. The total length of the grating is set to 400μm. The gap between waveguides is 80nm and the modulation depths of the input and output waveguide corrugations are 50 and 30nm respectively. All these values are also depicted in Fig. 3.

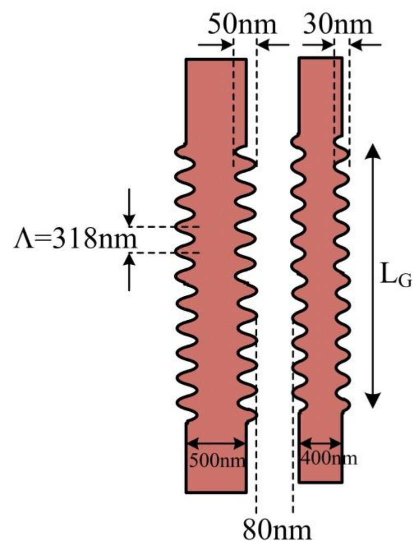
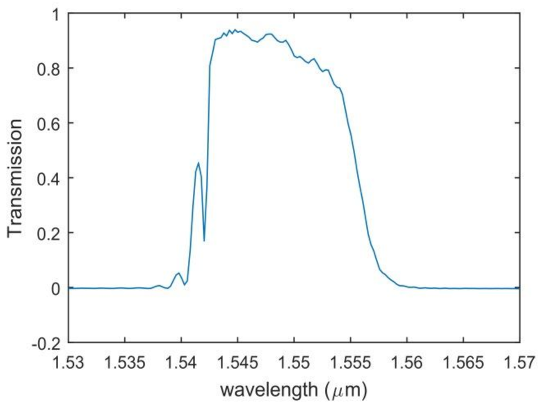


Figure 3: The Bragg grating and its structural parameters.

The most important part is designing the Bragg grating is the control of the amount of dispersion generated by this device. It is shown that by decreasing the chirp value, the dispersion increases, however, the bandwidth decreases and both of these factors can be controlled by chirping. Chirping the Bragg gating, varies the period of the structure according to the relation $\Lambda(z)=\Lambda_0+\Delta\Lambda z/L$. Λ_0 is the primary grating period and $\Delta\Lambda$ is the chirp factor. To remove the ripples in the response of the group delay and the resulting dispersion, we also use apodization functions, which serves as an envelope function for the corrugations. 2D-FDTD is also employed here to obtain the group delay of the structure.

The transmission and group delay versus wavelength for a grating with total length (L_G) of 400μm, chirp factor of 2.5nm and an apodization function of tanh type with a coefficient of 0.001 are illustrated in Fig. 4(a) and (b) respectively. As can be seen from Fig. 4(a), the transmission is larger than 0.8 for a relatively large bandwidth around 1550nm. As can be observed from Fig. 4(b), the group delay increases with wavelength which implies anomalous dispersion. The ripples in the group delay characteristic is suppressed to a much extent because of the apodization function we employed.



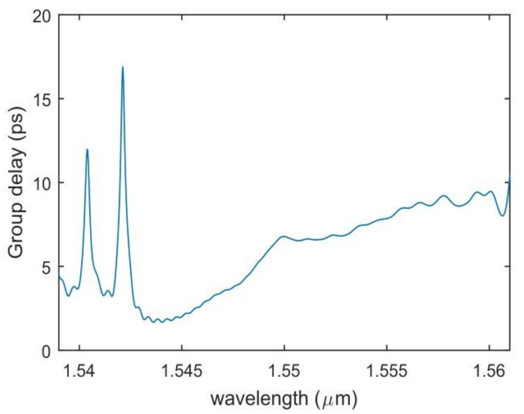


Figure 4: (a) Transmission and (b) group delay of the chirped Bragg grating versus wavelength.

Once the group delay (τ) is obtained, group velocity dispersion can be easily obtained by taking the derivative of the group delay versus wavelength as GVD=$d\tau/d\lambda$ and according to Fig. 4(b), GVD at 1555nm equals to 0.54ps/nm. However, this derivative is not accurate due to the fluctuations in group delay response and the functioning of the chirped grating must be evaluated in the compressor device.

C. Pulse compressor design

In the two previous subsections, we analyzed the crucial segments of the optical pulse compressor. In this subsection, we combine these segments to verify the functioning of the pulse compressor and investigate its results. 2D-FDTD simulations in employed as before to model the compressor. Two designs are presented here. For the first design, we assume an input pulse with FWHM of 5ps and power of 8W, nonlinear waveguide length of 3mm and a chirped Bragg grating with the following characteristics: L_G=250μm, $\Delta\Lambda$=2.5nm, apodization function: Blackman, apodization factor= 0.001.

The output pulse in illustrated in Fig. 5. As can be seen, the FWHM of this pulse is approximately 2ps implying a compression ratio of 2.5.

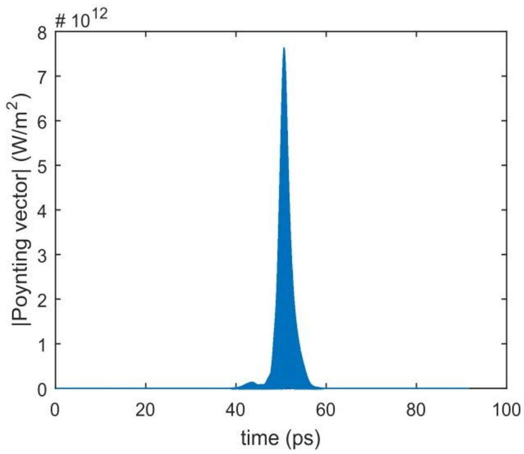


Figure 5: Output pulse versus time for the first pulse compressor design. FWHM of this pulse is approximately 2ps implying a compression ratio of 2.5.

In the presented design, we used a source power of approximately 8W and a nonlinear waveguide of 3mm which are both lower than the values reported previously (10W input pulse and waveguide length of 6mm [10]).

However, as stated previously, MoS_2 coating is expected to increase the Kerr nonlinearity by 2 orders of magnitude implying that the length could be enhanced further by designing the appropriate Bragg grating.

For our second design, we decrease the waveguide length even further to 1mm and apply an input pulse with a power of 8W and duration of 7ps and employ a grating with the following characteristics: L_G=400μm, $\Delta\Lambda$=2nm, apodization function: tanh, apodization factor=0.001. The chirp factor is reduced to further enhance the dispersion. Both the input and output pulses are illustrated in Fig. 6.

The output pulse FWHM is approximately 2ps and the compression ratio for this case is 3.5. Considering that the length of our design is much smaller than the previous ones, this compression ratio is acceptable. The tails of the output pulse broaden which is attributed to dispersion and is less than what is needed to compensate the phase of the first segment.

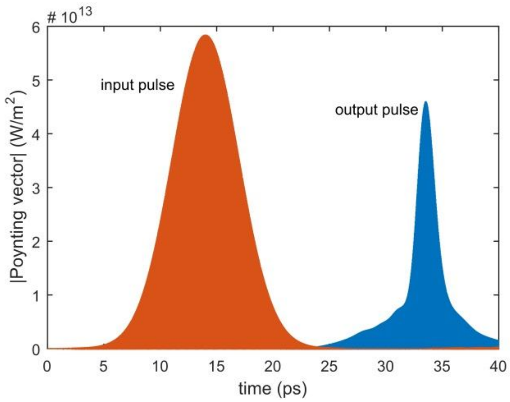


Figure 6: The input and compressed output pulses for the second design.

4. CONCLUSION

In this paper it is shown that by utilizing MoS_2 coated Si waveguides to enhance the nonlinearity and the resulting SPM, it is possible to design optical pulse compressors with smaller lengths and less input powers. Although this technique yields a much smaller waveguide length, however the controlling of the dispersion imposed by the chirped Bragg grating remains a challenge and often it is less that the required value for optimal pulse compression and designing novel chirped Bragg grating structures with higher anomalous dispersion values seems to be crucial for more compact, low power and highly efficient optical pulse compressors. Here in, we have designed a pulse compressor with compression ratio of 3.5 with a 1mm of nonlinear waveguide length and a total device length of less than 1.5mm.

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BIOGRAPHIES

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How to cite this paper:

A. Ahmadi Pour, H. Tezkhan, and H. Soofi "Optical pulse compression based on nonlinear silicon waveguides and chirped bragg gratings," *Journal of Electrical and Computer Engineering Innovations*, vol. 5, no. 1, pp. 19-23, 2017.

DOI: 10.22061/JECEI.2017.625

URL: http://jecei.srttu.edu/article_625.html