Efficient Two Photon Absorption for 400-nm Remote Optical Control at 2-µm Waveband in a Low-loss Multimode Silicon Waveguide

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Abstract: Efficient TPA for 400-nm range remote control at 2-µm waveband is experimentally realized with 8.9-dB ER by C-band pump using a low-loss multimode silicon waveguide, indicating fully utilized advantages at both C and 2-µm wavebands.

1. Introduction

Silicon photonics has developed rapidly in recent years and accounts for a great proportion in photonic integrated circuits. Apart from advantages like CMOS compatible, high density, low optical loss, and so on, silicon photonic platform is also attractive due to its colorful nonlinear effects and large nonlinear response. Nonlinearity in silicon, for example, stimulated Raman scattering, stimulated Brillouin scattering, and four-wave mixing, have been demonstrated in many applications such as all-optical signal processing [1], on-chip amplifiers and lasers [2], soliton comb generation [3] and so on. Among them, two-photon-absorption (TPA) is one common nonlinear effect suffered by integrated silicon circuits, resulting in significant power absorption at high power levels, which may be harmful for amplification or communication systems. Nevertheless, TPA effect can also be beneficial, so as to enable applications like all-optical switching [4], detection [5], and modulation [6]. Nondegenerate TPA (ND-TPA) can be considered as a TPA process, in which the material absorbs two photons at different wavelength simultaneously, rather than degenerate TPA absorbing the same photons.

Meanwhile, TPA is usually smaller with higher threshold at longer wavelengths like 2-µm waveband compared with e.g. C-band. As for silicon PIC, at 2-µm waveband, the intrinsic absorption is also smaller while the modulation and detection is highly limited. Thus, it is highly useful if one can utilize the silicon platform advantages at C-band with better modulation, detection and so on, to improve the performance at 2-µm waveband, which is exactly our objective in this study based on ND-TPA with efficient remote control between C and 2-µm wavebands.

In this work, we experimentally realized the ND-TPA based 400-nm range remote optical signal processing between C and 2-µm wavebands. High efficient control is obtained for 2-µm waveband signal with 8.9dB extinction ratio (ER) when injecting C-band light of 27dBm as a pump into a low-loss long silicon waveguide, indicating strong ND-TPA effect between two light sources, showing great potential for remote all-optical signal processing.

2. Optimized waveguide structure and experimental system

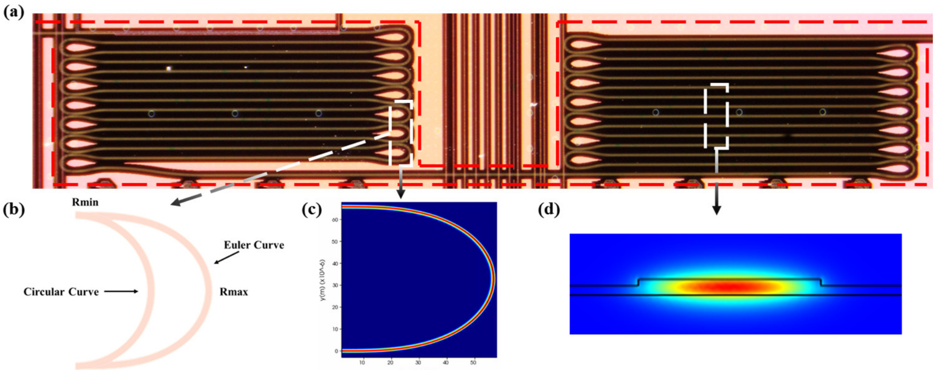

Fig. 1. (a) Microscope image of fabricated long waveguide (inside the red dot line). (b). Comparison between Euler curve and circular curve. (c) light field distribution in a Euler curve waveguide. (d) light field in a multi-mode waveguide section.

To achieve a high efficiency ND-TPA, the waveguide should be designed with low propagation loss, avoiding power scattering which may decrease nonlinear effect. Moreover, the total length of waveguide should be large, in order to increase the interaction distance between light field and the waveguide, which may increase the nonlinear efficiency as well. According to this principle, we designed and fabricated a long silicon waveguide, aimed to achieve the goal of low loss and high nonlinear efficiency. Fig. 1(a) shows the long waveguide fabricated for the ND-TPA experiment. It is a rib waveguide and has a total length of 12.3cm. The whole waveguide is mainly composed of multi-mode straight waveguide connected with 180° Euler curve bend waveguide. The curvature of a Euler curve changes linearly with its curve length, as shown in Fig. 1(b), by connecting the minimum radius end of the Euler curve waveguide with straight waveguide, it will help to decrease the mode crosstalk and propagation loss, due to the smooth change of waveguide curvature at the joint. Fig. 1(c) shows the light field of a Euler curve waveguide, it can be indicated that the waveguide confines the light tightly. The Euler curve we adopted in our waveguide has a maximum radius of 1600nm and a minimum radius of 50nm. Besides, multi-mode waveguide is adopted to reduce sidewall scattering loss, and the width of core waveguide, height of rib is 2500nm and 130nm respectively. The whole waveguide is fabricated in a SOI wafer with a 220nm thick silicon layer, by CompoundTek, Singapore.

We experimentally test the whole loss of this waveguide in C waveband at 1550 nm, with two lensed fiber coupled light in and out of the waveguide on chip. In this way, we also test the whole loss of another waveguide, which has all the same structures with this 12.3 cm long waveguide, however, with a length of 10.0 cm. This aims to figure out the attenuation, exclude other loss such as coupling. Finally, the test result of average loss difference is about 0.74 dB, indicating that the attenuation of this waveguide is about 0.32 dB/cm at 1550 nm, which is at a very low level, shows a good propagating performance. Besides, attenuation in 2μm band is also tested, with a value of 0.87 dB/cm.

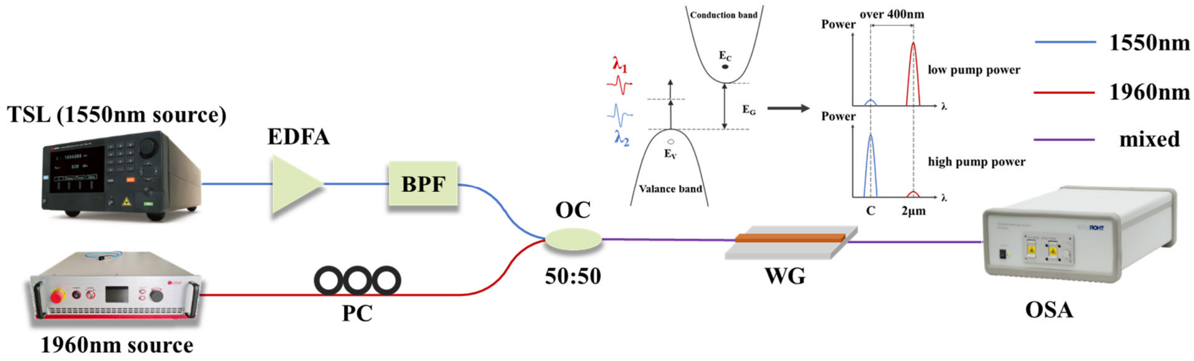

Fig. 2. Schematic diagram of the ND-TPA experimental setup. The blue, red and purple line represent the 1550nm, 1960nm and mixed light path respectively. Graph upside the WG is mechanism of the ND-TPA. TSL: Tunable laser source, EDFA: Erbium-doped optical fiber amplifier, BPF: Band pass filter, PC: Polarization controller, OC: Optical coupler, WG: Waveguide on SOI chip, OSA: Optical spectrum analyzer.

The experimental setup for ND-TPA is shown in Fig. 2. For C-band light, we use a tunable laser source (Santec TSL-710), and set its wavelength as 1550nm. For 2-μm waveband light, we use a 1960-nm single frequency laser. The 1550-nm light source will be first amplified by EDFA, and then passes through BPF, in order to filter ASE noise generates by the EDFA. The high power 1550-nm light acts as pump light and the relatively low power 1960-nm light acts as signal light. After amplifying by the EDFA, 1550-nm pump light and 1960-nm signal light will be combined by a 50:50 optical fiber coupler to become the mixed light. The light power coupled in the WG we mentioned in the following part, is the power detected on output port of this coupler. The mixed light will be coupled from OC to the waveguide on SOI chip through a lensed fiber.

After coupling into the waveguide, two light sources at different wavelength will excite extremely high nonlinear absorption inside the chip, of which dominant contribution to its absorption for the weaker signal light comes from cross-interaction between the pump and signal. The mixed light will then be coupled out of the waveguide, also through a lensed fiber. We use a wideband optical spectrum analyzer (Thorlabs OSA-203C) to measure the spectrum and power of output light.

3. Results and analysis

In the experiment, we set the 1960nm light power as a constant value of 10 dBm, and change the power of pump light, 1550 nm source, from 0 to 27 dBm, to observe the ND-TPA phenomenon quantificationally. The results are shown in Fig. 3 as followed.

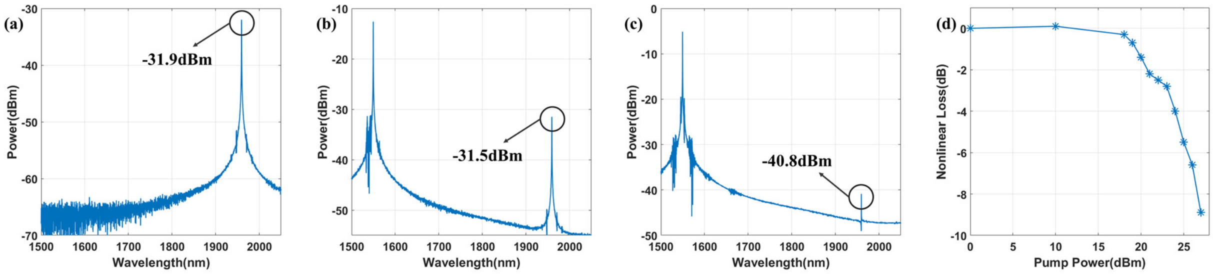

Fig. 3. (a) Spectrum of light with no 1550-nm pump. (b) spectrum of light with 1550 nm pump of 10 dBm. (c) spectrum of light with 1550-nm pump of 27 dBm. (d) curve of nonlinear loss caused by ND-TPA varying with pump power.

In Fig.3, the spectrums of different pump power are shown. The 1550nm pump power, coupled in the SOI waveguide, of Fig. 3(a), (b), (c) are 0, 10 dBm, and 27 dBm respectively. And the 1960-nm signal power measured by spectrum analyzer in these three figures are -31.9 dBm, -31.5 dBm, and -40.8 dBm, as labelled near the peak of the curve. The power values indicated in the spectrum are relatively low considering the low-loss waveguide, this is due to the reason that output light passes through an optical attenuator before being measured, in order to protect OSA from high power light damage. In Fig. 3(d), we measure the signal power under different pump power, and compare it with the value of which the pump power is 0. The y-axis is the difference value between the signal power under certain pump power, and, the signal power where there is no pump. Obviously, this difference is nonlinear loss excited in the silicon waveguide, caused by ND-TPA. It can be indicated in Fig. 3(d) that, the nonlinear loss remains at a low value under low power pump, and increases rapidly when pump power exceeds 18dBm, which means strong TPA occurring in the waveguide after pump power reaching this level. Moreover, under the maximum power we could get (27 dBm), the nonlinear loss of 1960-nm signal light increases up to 8.9 dB, indicates that the ND-TPA has brought a large extinction ratio to the signal power, in such a wide wavelength range from C to 2-μm waveband. In this way, remote optical signal processing can be achieved through TPA, and advantages of high-speed modulation, high-sensitive detection in C waveband can be transferred to 2 μm, extending applications and performance of this new waveband.

4. Conclusion

We experimentally demonstrated the efficient nondegenerate two photon absorption between C waveband and 2μm waveband continuous wave light source, at the first time. A large extinction ratio of 1960 nm CW signal light up to 8.9 dB is observed through the spectrum, which is caused by ND-TPA between the high power 1550nm pump light and signal. With this promising performance, we believe this nonlinear phenomenon can be adopted to various applications such as all-optical modulation, and switching under SOI platform, showing great potential for remote optical signal processing.

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5. References

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