Design the Structure of Vertical Multilayer Hybrid Silicon Waveguide to Work in Anomalous Dispersion Region

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Keywords: Waveguide, Dispersion, Slot Waveguide, Silicon Photonics, Nonlinear Optical Device, Integration Optics.

Abstract: In order to decrease the dispersion of the silicon vertical slot waveguide, we propose a vertical multilayer hybrid silicon waveguide. The optical mode distribution of the multilayer waveguide is simulated by a finite element method. By a proper design of the waveguide parameters, the dispersion of waveguide can in the range of ±300 ps/nm/km in 1510-1590 nm, with one zero-group-dispersion point in the C band. This waveguide can be an alternative in on-chip nonlinear application, such as all optical signal processing.

1 INTRODUCTION

Silicon photonics has been an important branch in modern optics. Due to its compact size and rich nonlinear properties, silicon waveguides are promising in on-chip signal transmission and all kinds of signal processing. One main obstacle of the application of silicon waveguides is its relatively large waveguide dispersion, which induces optical pulse broadening in signal transmission and phase-mismatch in some nonlinear parametric process. Conventionally, the process of efficient four wave mixing occurs in a waveguide with anomalous dispersion. Although the material dispersion of crystalline silicon is large and normal, it can be compensated by the structural dispersion through optimization of waveguide structure parameters. For silicon strip waveguide, broad-band anomalous dispersion has been realized(Turner et al., 2006) and optical parametric gain has been experimentally demonstrated(Foster et al., 2006).

Silicon slot waveguide is proposed in 2004(Almeida et al., 2004) and broadly investigated in the last decade(Zengzhi et al., 2015, Huang and Xia, 2016). Combining high quality nonlinear cladding material with silicon slot waveguide, the hybrid slot waveguide is potential in on-chip all-optical signal processing. A lot of researches relate to the dispersion engineering of silicon slot waveguides to achieve anomalous dispersion in telecommunication wavelength to near infrared wavelength. Most researches are based on a horizontal slot waveguide structure, that is, the direction of the slot is horizontal to the silica substrate(Zhang et al., 2010b, Zhang et al., 2010a). For vertical slot waveguides, it’s difficult to tailor the dispersion to the anomalous region. Some designs tailor the dispersion by shifting the slot position off the waveguide centre of using dual-slot, however, that leads to in some working wavelengths, the optical field are not centred in the slot region(Zhu et al., 2012).

In this article, we propose a novel hybrid vertical slot waveguide structure intended to achieve broad-band anomalous dispersion in telecommunication wavelength and near infrared wavelength. This novel vertical slot waveguide structural is like a multilayer structure in horizontal direction. By choosing appropriate low index material, the hybrid silicon slot waveguide can have a zero-group-dispersion wavelength in the telecommunication region. What’s more, using this novel waveguide, a large portion of the optical energy contains in the low-index slot and cladding region, which is beneficial in reducing the two photo absorption and free carriers absorption in the silicon layer.

2 WAVEGUIDE STRUCTURE

Before designing the waveguide structure, we first take a look at the two familiar silicon waveguides, channel waveguide and slot waveguide. The

Huang Z., Yuan S. and Xia J.
Design the Structure of Vertical Multilayer Hybrid Silicon Waveguide to Work in Anomalous Dispersion Region.
DOI: 10.5220/0006220802940297
In *Proceedings of the 5th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2017)*, pages 294-297
ISBN: 978-989-758-223-3

dispersions of both waveguides have been investigated by previous works. It's known that silicon has a large and normal dispersion near 1550nm. Fortunately, silicon waveguide has a strong confinement of light, which induces large structural dispersion. By optimizing waveguide structure parameters, the structural dispersion can be anomalous dispersion and compensate the material dispersion, thus obtaining anomalous waveguide dispersion.

We use Lumerical mode solution software to simulate the waveguide dispersion. The material dispersions of silicon and SiO_2 are taken into consideration, in the form of Sellmeier Equation. Fig.1 shows the dispersion of a channel waveguide. The waveguide is on a 340nm SOI substrate. The width of the waveguide is 500nm. We can see that there is a zero group velocity dispersion point in 1567nm. For wavelength larger than 1567nm, the channel waveguide shows anomalous dispersion.

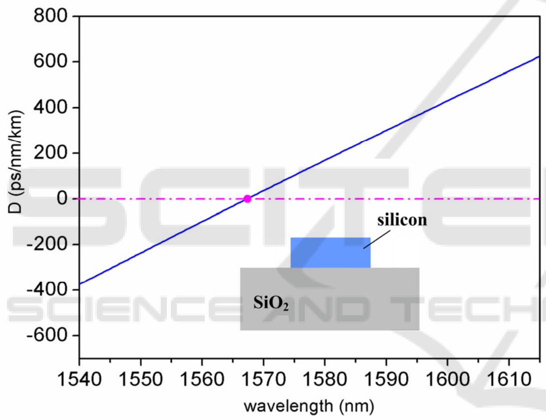

Figure 1: Simulated dispersion curve of a silicon channel waveguide, with a size of 500nm × 340nm (width × height).

However, it's difficult to achieve anomalous dispersion in vertical silicon slot waveguides. Fig. 2 is the dispersion curve for a slot waveguide. The waveguide parameters are as following, h=340nm, W_{Si}=200nm and W_{slot}=100nm. The total width of the slot waveguide is 500nm, same as the channel waveguide calculated above. It can be seen that the vertical slot waveguide has a large and normal dispersion in the wavelength from 1610-1820 nm.

Compared Fig.2 with Fig. 1, we can conclude that the insertion of the 100-nm slot in the middle of the channel waveguide makes a big difference to the waveguide dispersion. This is because the air slot breaks the continuity of the electric field component E_x of the TE mode.

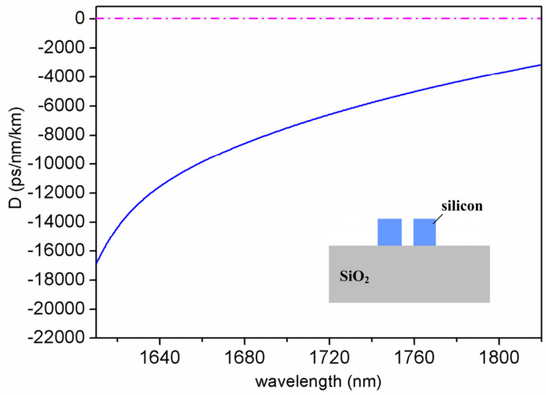

Figure 2: Simulated dispersion curve of a silicon vertical slot waveguide. The top silicon layer thickness is 340nm. The widths of the slot and silicon rail are 100nm and 200nm, respectively.

In order to decrease the normal dispersion of the vertical slot waveguide, two ways are demonstrated to be feasible. i). Design a waveguide with larger cross section. That means increasing the thickness of the top silicon and the width of the waveguide. ii). Reduce the refractive index difference between the silicon and slot region. Both of these two ways are supposed to alleviate the abrupt change of the optical mode induced by the waveguide boundary.

3 MODAL PROFILE

Following these two designing principles, we propose a vertical multilayer hybrid silicon waveguide, shown like Fig. 3. It can be seen as a silicon slot waveguide with a rectangular low-index cladding. W and h denote the width and height of the cladding, respectively. W_{Si} and W_{slot} represent the width of the silicon rail and the width of the central low index region.

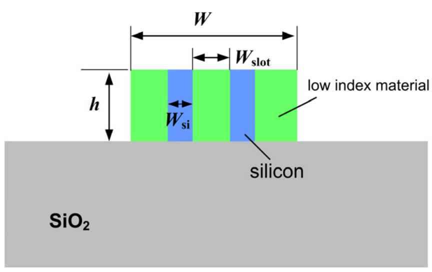

Figure 3: A schematic of the vertical multilayer hybrid silicon waveguide (in cross view).

An optical mode simulation is performed using the COMSOL Multiphysics software. The simulation region is 4μm×4μm. The simulation boundary is set as scattering boundary condition. The waveguide parameters are W=700 nm, h=500 nm, W_{Si}=100 nm and W_{slot}=200 nm. The refractive index of the low index material is set as 2.4, so the electric field in the low index region is enhanced by a factor of 1.45 on the Si-slot interface. The effective index of the multilayer waveguide is 2.23 in 1550nm. Fig. 4 is the electric field distribution of the fundamental quasi-TE mode. We can observe that a characteristics slot mode exists in the proposed waveguide, in which the electric field in the low index slot region is increased. The electric field enhancement can also be reflected by a 2D cross line view, as the yellow line in Fig. 4 shows.

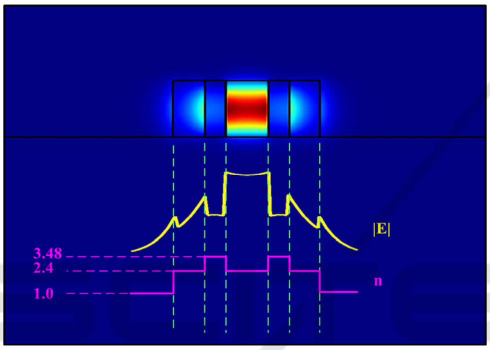

Figure 4: Electric field distribution of the multilayer waveguide.

Compared to the traditional silicon slot waveguide, the multilayer vertical waveguide has smaller W_{Si} and larger W_{slot}, due to two additional low index regions. This feature is fascinating in nonlinear application based on silicon slot waveguide, because the two photon absorption effect in silicon is suppressed and it is promising to achieve a high figure of merit (FOM)(Zhang et al., 2015).

4 WAVEGUIDE DISPERSION

We calculate the dispersion of the multilayer waveguide, shown as Fig.5. For low index material refractive index n=2.4, the waveguide dispersion is less than ±300 ps/nm/km in 1510-1590 nm, with a zero-group-dispersion point in 1542 nm. For wavelength longer than 1542 nm, the multilayer waveguide have anomalous dispersion.

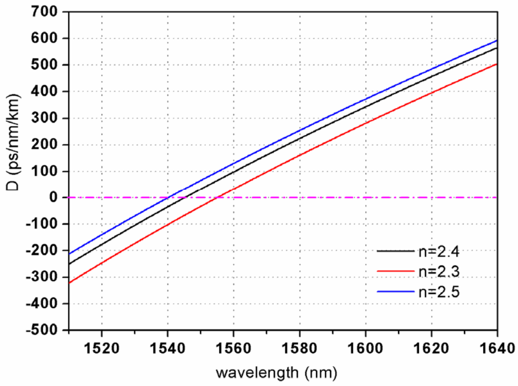

Figure 5: Waveguide dispersion curves for n=2.3, 2.4 and 2.5, respectively. The other parameters are W=700 nm, h=500 nm, W_{Si}=100 nm and W_{slot}=200 nm.

Next we investigate how the waveguide parameters influence the dispersion of the multilayer waveguide. Varying n from 2.3 to 2.5, we can see in Fig.5 that if n becomes larger, the dispersion curve moves upwards and the zero-group-dispersion point moves to shorter wavelength.

The waveguide height has small influence to the waveguide dispersion. This is shown in Fig.6.

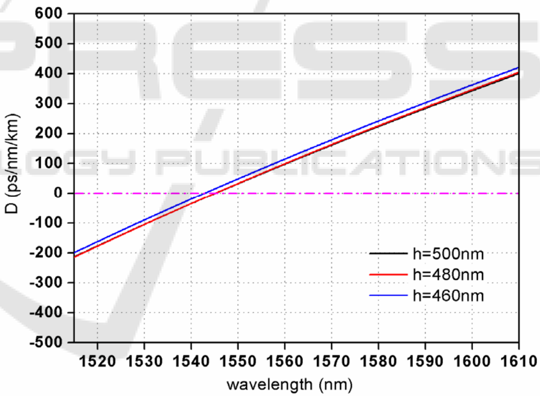

Figure 6: Waveguide dispersion curves for h=460nm, 480nm and 500nm, respectively. The other parameters used for simulation are W=700 nm, W_{Si}=100 nm, W_{slot}=200 nm and n=2.4.

The dispersion curve for various W_{Si} is depicted in Fig.7. The figure shows that W_{Si} is an important factor that decides the waveguide dispersion. For W_{Si}=90 nm, the multilayer waveguide remains in anomalous dispersion region for the whole calculation wavelength. However, W_{Si}=120 nm, the waveguide works in normal dispersion.

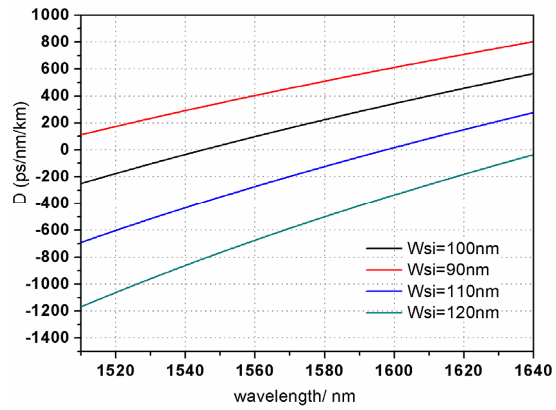

Figure 7: Waveguide dispersion curves for W_{Si}=90nm, 100nm, 110nm and 120nm, respectively. The other parameters used for simulation are W=700 nm, h=500 nm, W_{slot}=200 nm and n=2.4.

5 CONCLUSIONS

In this paper, we propose a vertical multilayer silicon hybrid waveguide, to overcome the large normal dispersion of the vertical silicon slot waveguide. By proper design, the dispersion of waveguide can in the range of ±300 ps/nm/km in 1510-1590 nm. This kind of waveguide can be as a nonlinear optical waveguide, and find its applications in on-chip all optical signal processing. The multilayer waveguide provides additional flexibility in tailoring the dispersion. A lower, flatter dispersion can be obtained by further optimization.

ACKNOWLEDGEMENTS

This work is supported in part by the Major State Basic Research Development Program of China under Grant 2013CB632104 and Grant 2013CB933303, and in part by the National Natural Science Foundation of China under Grant 61177049 and Grant 61335002.

REFERENCES

Almeida, V. R., Xu, Q., Barrios, C. A. & Lipson, M. 2004. Guiding and Confining Light in Void Nanostructure. *Optics Letters,* 29**,** 1209-1211.

Foster, M. A., Turner, A. C., Sharping, J. E., Schmidt, B. S., Lipson, M. & Gaeta, A. L. 2006. Broad-Band Optical Parametric Gain on a Silicon Photonic Chip. *Nature,* 441**,** 960-963.

Huang, Z. & Xia, J. 2016. Sub-50-Nm Wide Slot Waveguides with Good Optical Isolation on Silicon on Insulator. *Optical Engineering,* 55**,** 087102-087102.

Turner, A. C., Manolatou, C., Schmidt, B. S., Lipson, M., Foster, M. A., Sharping, J. E. & Gaeta, A. L. 2006. Tailored Anomalous Group-Velocity Dispersion in Silicon Channel Waveguides. *Optics Express,* 14**,** 4357-4362.

Zengzhi, H., Zhang, Y., Zeng, C., Li, D., Nisar, M. S., Yu, J. & Xia, J. 2015. High Confinement Factor Ridge Slot Waveguide for Optical Sensing. *Ieee Photonics Technology Letters,* 27**,** 2395-2398.

Zhang, L., Yue, Y., Beausoleil, R. G. & Willner, A. E. 2010a. Flattened Dispersion in Silicon Slot Waveguides. *Optics Express,* 18**,** 20529-20534.

Zhang, L., Yue, Y., Xiao-Li, Y., Wang, J., Beausoleil, R. G. & Willner, A. E. 2010b. Flat and Low Dispersion In Highly Nonlinear Slot Waveguides. *Optics Express,* 18**,** 13187-13193.

Zhang, W., Serna, S., Dubreuil, N. & Cassan, E. 2015. Nonlinear Optimization of Slot Si Waveguides: Tpa Minimization With Fomtpa up To 4.25. *Optics Letters,* 40**,** 1212-1215.

Zhu, M., Liu, H., Li, X., Huang, N., Sun, Q., Wen, J. & Wang, Z. 2012. Ultrabroadband Flat Dispersion Tailoring of Dual-Slot Silicon Waveguides. *Optics Express,* 20**,** 15899-15907.