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Numerical investigation and design of optical on chip waveguide with engineered dispersion for generation of supercontinuum based frequency combs

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Abstract

In this paper, with dispersion engineering, two waveguides with silicon core and SiO₂ cladding are proposed to generation the supercontinuum spectrum and optical frequency combs. By injecting a pulse with a peak power of 800 (W) and a pulse duration of 50 (fs), the output supercontinuum spectrum is obtained from a wavelength of 1100 (nm) to 4000 (nm). Also, by applying a maximum power of 1 KW and a pulse width of 100 (fs), optical frequency combs based on a supercontinuum with a broadband frequency combs have been obtained. Our proposed structure has good potential for engineering and achieving flatness dispersion which there are two zero dispersion wavelengths at 1890 (nm) and 2850 (nm). This flat dispersion can be very useful to achieve the desired output spectrum. Due to the materials used and the flat structure of the proposed waveguides, these waveguides can be used for integrated optical circuits as well as applications in optical communications, spectroscopy, and sensors.

Key words: supercontinuum generation, frequency comb generation, dispersion, zero-dispersion wavelength, highly nonlinear.

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Introduction

Today, the need to use high-capacity applications such as high-capacity data transmission such as high-resolution video, artificial intelligence, and 5G technologies has led to a high-capacity transmission network. Optical networks have enough potential to reply for these needs due to their large bandwidth. In addition, the capacity of optical networks is increasing rapidly. Due to the high bandwidth, optical signal processing (OSP) techniques are considered a suitable platform for processing high data capacities (Qin. Jun et al.2020; Dupont et al. 2012; Husakou. A. V. and J. Herrmann 2001). OSP systems are used in various optical fields such as analog and digital signal processing, nonlinear applications, and fast and advanced data modulation. They are essential for the processing of high-speed fiber-optic communication signals (Willner et al. 2019).

Most recently, there is urgent need for compression and device miniaturization in optical circuits, which can be achieved by using the nonlinear effects of structures containing silicon (Li et al. 2018), Hydex (Moss et al. 2013), SiN (Tan et al 2018; Frigg et al. 2019), AlN (Gong et al. 2018), diamond (Amirhassan et al. 1019), III-V semiconductor (Pu et al. 2016; Hu et al. 2018; Chang et al. 2018), and chalcogenide (Karami et al. 2017; Alizadeh and Seifouri 2017; Seifouri and Alizadeh 2018; Alizadeh and Seifouri 2019). Silicon-on-insulator (SOI) waveguide is considered as an important substrate in compact circuits due to its high nonlinear properties and compatibility with CMOS integrated circuits.

There are several ways to increase the nonlinear coefficient of the structure. One of the methods is a strong optical field confinement in the structure, which increases with a high index contrast between the core and the cladding, which results in a highly efficient four-wave mixing (FWM) process that is important in many applications (Pu et al. 2017; Oxenlowe et al. 2012). The FWM phenomenon is

especially important for phase-sensitive processing where signal and idler wave interference is desired (Da et al. 2016). One of the most important applications of nonlinear effects is supercontinuum spectrum generation (SCG) as well as the optical frequency comb generation (FCG).

The supercontinuum is the broadening of a very short pulse that enters to input of a waveguide or fiber with a high nonlinear coefficient. The interaction of various parameters such as dispersion and nonlinear effects such as self-phase modulation, Raman effects, and four-wave mixing, etc., cause this expansion. Typically, the broad SCG is formed from compressing of solitons and soliton breaking effect in the anomalous dispersion region, and then the propagation of the dispersive wave (Dupont et al. 2012; Husakou and Herrmann 2001). SCG sources include wide and flat output spectra that have been used extensively in spectroscopy (Ke et al 2009; Eggleton 2011), microscopy (Aggarwal and Sanghera 2002), imaging (Dudley et al. 2006), metrology, tomography, pulse compression, fingerprinting, and sensors (Dudley and Taylor 2009; Paul et al. 2019). Especially the infrared spectral range is very important because the molecules of the most of materials oscillate in this region (Dai et al. 2018). The SCG has been extensively studied in nonlinear media such as fibers and photonic crystal fibers. However, the waveguides that can be implemented on chips have recently attracted much attention (Yoon et al. 2017; Safioui et al. 2014). In addition to optimizing the optical waveguide structure, the appropriate pumping wavelength and maximum input pulse power can be used to broaden the pulse. However, it should be noted that in practice, there are limitations for each. The dispersion profile also plays an important role in the width and flattening of the SCG, especially if the pumping wavelength is close to the zero dispersion wavelengths (ZDW), which can be adjusted based on the waveguide structure in urgent regime. To increase the width of the produced

spectrum, pumping is injected to the anomalous dispersion zone, which produces solitons and four-wave mixing (Møller et al. 2015; Luo et al. 2017). The width of the supercontinuum spectrum in fibers is usually greater than in waveguides and fibers have lower losses. However, to produce a wide spectrum, the effective length of the waveguides is shorter than that of the fibers, and the flat nature of the waveguides allows them to be implemented on chips (Yu et al. 2014; McCarthy et al. 2013; Ma et al. 2013).

The optical frequency comb (OFC) consists of a spectrum with equal frequency lines, each of which has a relatively constant phase so that the spectrum appears as a comb. This OFC spectrum can be employed in many applications such as astronomy (Obrzud et al. 2019), optical communications (Feifle et al. 2014), microwave photonics (Xue et al. 2018), and other fields. Several methods have been proposed for creating frequency combs with a flat spectrum for use in high-capacity optical communications (Hu and Oxenløwe 2021). The first method is to use combs based on electro-optical modulators. However, this method usually involves bulky components, and has limited comb lines spanning over a few nanometers or exhibit the triangular spectrum (Company and Weiner 2014; Zhang et al. 2019). The second method is to use integrated mode-locked lasers. In this method, the optical linewidth of the mode-locked laser is usually too large for coherent optical communication (Zhang et al. 2016; Liu et al. 2020). The third method is to use the nonlinear microresonator-based Kerr frequency combs. In this method, the spacing of frequency comb depends on the free spectral range (FSR) of the used microresonator, where its tunability is limited (Kippenberg et al. 2018). The fourth method is based on SCG by injecting a laser pulse into a fiber or optical waveguide suitable for practical application because of the long time stability of the comb (Obrzud et al. 2018; Deng et al. 2022). Highly nonlinear fiber with

normal dispersion is a desirable method for generation of broadband OFC spectrum (Takushima et al.1998). However, such a fiber must be hundreds of meters long and should exhibit a normal, almost near zero-dispersion along this length (Myslivets et al.2012). The production of long fiber with the mentioned characteristics has serious challenges in manufacturing technology. One method is to use high nonlinear optical integrated circuits based waveguides which not only using materials with high nonlinear coefficients but also the high optical limitation can be achieved in these waveguides; thus, the desired length in these structures is significantly reduced. In this paper, by dispersion engineering and investigating the effect of dimensions on the dispersion profile, two silicon waveguides are proposed to generation of supercontinuum spectrum and frequency combs based on SCG. Due to the materials used and the flat structure of the proposed waveguides, these waveguides can be used for integrated optical circuits as well as applications in optical communications, spectroscopy, and sensors.

theory

The nonlinear Schrödinger equation can be solved numerically using the split-step Fourier method to study the generation of supercontinuum spectrum and frequency combs. The simplified form of this equation is as follows (Alizadeh and Seifouri 2020):

$$\frac{\partial A}{\partial Z} = (\hat{D} + \hat{N})A \quad (1)$$

Where D represents the linear part and N represents the nonlinear part of this equation. The value of D is obtained from the following equation.

$$D = -\frac{\alpha(w)}{2} + \sum_{n \geq 2} \beta_n \frac{i^{n+1}}{n!} \frac{\partial^n}{\partial t^n} \quad (2)$$

In equation 2, α , represents the waveguide loss coefficient, which can be neglected due to the low waveguide length. β_n ($n \geq 2$) Indicates the various orders of dispersion that can be obtained from the following equation (Zho and Brown 2002; Ming et al. 2010).

$$\beta_m = \left(\frac{d^m \beta}{d\omega^m} \right)_{\omega=\omega_0} \quad (m = 0, 1, 2, \dots) \quad (3)$$

In this equation, ω_0 represents the pumping wavelength. In addition, the nonlinear part of the equation1 is obtained from the follows (Karpisz et al. 2015):

$$N = i\gamma \left(1 + \frac{i}{\omega_0} \frac{\partial}{\partial t} \right) \int_{-\infty}^{\infty} R(T') |A(Z, T - T')|^2 dT' \quad (4)$$

In this equation, A is the input pump envelope, and γ is the nonlinear coefficient and is obtained from the following equation:

$$\gamma = \frac{\omega_0 n_2}{c A_{\text{eff}}} = \frac{2\pi n_2}{\lambda A_{\text{eff}}} \quad (5)$$

In the above equation n_2 , the nonlinear refractive index is related to the Kerr effect. C is the speed of light in a vacuum. A_{eff} is the effective mode area at the central wavelength for the propagation mode and λ is the pumping wavelength. Also, in Equation 4, $R(T')$ is a function of the Raman response and is obtained from the following equation (Ghanbari et al. 2018).

$$R(T') = (1 - f_R) \delta(T) + f_R h_R(T) \quad (6)$$

Where the value of $f_R = 0.1$ and $h_R(T)$ is obtained from the following equation:

$$h_R(T) = \frac{\tau_1^2 + \tau_2^2}{\tau_1 \tau_2^2} \exp\left(-\frac{t}{\tau_2}\right) \sin\left(\frac{t}{\tau_1}\right) \quad (7)$$

Where the value of $\tau_1=10$ fs and $\tau_2=3$ ps for Si (Ghanbari et al. 2018).

The group velocity dispersion $D(\lambda)$ is calculated using the propagation mode wavelength-dependent effective refractive index through the following equation

$$D(\lambda) = -\frac{\lambda}{c} \frac{\partial^2 \text{Re}(n_{eff})}{\partial \lambda^2} \quad (8)$$

Where $\text{Re}(n_{eff})$ is the real part of the effective refractive index and determined by using of the Sellmeier equation (Agrawal 2013).

Dispersion engineering and waveguide design

We have designed two waveguides with silicon core and SiO₂ cladding to produce supercontinuum spectrum and frequency combs. To achieve the final structure, we have used the effect of waveguide dimensional changes on dispersion and dispersion engineering. Fig1 shows the structure of the two proposed waveguides. The first structure in Figure 1(a)-(b) is very familiar, while the second structure is suitable for flat dispersion applications (Guo et al. 2019).

Fig1(e) shows the dispersion profile of the first structure. In this structure, the height h adjust 300 (nm), and the width w is equal to $w = 1000$ (nm). The curve has two zero-dispersion wavelengths around the wavelengths of 1980 (nm) and 2800 (nm). Fig2 shows the dispersion profile of structure 2, in which 2 (a), 2 (b), 2 (c), and 2 (d) correspond to the heights h_1, h_2, h_3, h_4 , respectively, and Fig2(e) is related to width changes of the waveguide.

The selected dimensions for structure two are shown in Table 1. This structure has two zero-dispersion wavelengths in 1890 (nm) and 2850 (nm) in the selected dimensions. However, the maximum dispersion in its anomalous region is much

less than in structure 1, which confirms the flatness of the dispersion curve in structure 2 compared to structure 1.

Fig1: The waveguides studied in this research (a) and (b) the shape and mode profile of the first structure, (c) and (d) the structure and mode profile of the second proposed structure and (e) Dispersion index of structure 1, in this structure, the size of height h is equal to 300 (nm), and the size of width w is equal to $w = 1000 \text{ (nm)}$. The curve has two zero-dispersion wavelengths around the wavelengths of 1980 (nm) and 2800 (nm).

(a)

(b)

(d)

(e)

Fig2: Dispersion profiles of structure 2, (a) Dispersion changes with respect to h_1 , (b) Effect of h_2 varying on dispersion profile, (c) Dispersion changes with respect to h_3 , (d) h_4 and (e) w .

Table 1
Design parameters of the proposed sensor.

Parameter	h_1	h_2	h_3	h_4	w
Value	200(nm)	360(nm)	390(nm)	540(nm)	1100(nm)

By numerically solving Equation 1 by the split-step Fourier method, one can observe the spectrum of generated supercontinuum spectra in the structure and properties of the FCG. To investigate the supercontinuum spectrum, an input pulse with a power of 800 (w) and a pump pulse width of 50 (fs) is injected to the input of waveguide 1. The value of the effective mode area in this structure is $0.33 \mu m^2$ which, according to the nonlinear coefficient of silicon $n_2 = 12 \times 10^{-14} cm^2 w^{-1}$ at about of 1900 nm (Bristow et al. 2007), the value of the nonlinear coefficient is equal to $\gamma = 115.93 m^{-1} w^{-1}$ is obtained. The supercontinuum spectrum and the corresponding spectrum evolution are shown in Fig3. This spectrum is prepared from wavelengths of 1100 (nm) to more than 4000 (nm).

For use in optical communications and the production of supercontinuum based frequency combs, the output spectrum is also simulated by numerically solving the Schrödinger equation at a pumping wavelength of 1550 (nm) in the normal dispersion region. To create effective interactions between dispersion and nonlinear effects, the waveguide length is considered to be 8 (mm) in this case. The maximum input power 1 (KW) with a pulse width of 100 (fs) is considered, where Equation 1 can be considered simpler (Liu et al. 2007; Muslu G. and Erbay 2005).

Fig4 shows the spectrum corresponding to the observed ultra broadband comb obtained via the structure1. There are several sharp peaks in the spectrum, which

indicates the ability to frequency combs generation in this structure (Goji et al. 2021; Enomoto et al. 2016; Yoshii et al. 2019).

Fig3. supercontinuum spectrum generated in structure 1, (a) supercontinuum spectrum with a pumping wavelength of 1890 (nm), (b) spectrum evolution.

Fig4: Frequency comb spectrum generated in structure 1 with pumping wavelength of 1550 (nm).

To generate supercontinuum spectrum in structure 2, an input pulse with a peak power of 800 (w) and a pulse width of 50 (fs) at a wavelength of 1890 (nm) is injected to a 0.8mm waveguide input. The effective area of mode in this structure is $0.4\mu\text{m}^2$, and the nonlinear coefficient is calculated like the first structure, the

value of which is $\gamma = 99.68 \text{ m}^{-1} \text{ W}^{-1}$. Fig. 5(a) and (b) show the mid-IR spectral broadening and pulse evolution in proposed waveguide2.

Fig5. supercontinuum spectrum generated in structure 2, (a) supercontinuum spectrum with a pumping wavelength of 1890 (nm), (b) pulse evolution.

Fig6: Frequency comb spectrum generated in structure 2 with pumping wavelength of 1550 (nm).

As can be seen in this figure, the output spectrum is normal and flat at wavelengths between 1000(nm)-1800(nm) and can be seen blue and red shifted solitons that cause spectral broadening from 1100(nm) to 3800(nm).

Fig 6 also shows the comb properties of waveguide 2 by numerically solving Eq.1 and injecting an input pulse at the wavelength of 1550 (nm). The comb properties of the output spectrum of waveguide 2 can be observed in this figure like fig 4.

By comparing the two output spectra related to frequency combs, it is observed that the structure2 is more suitable for generation of flat frequency combs in optical communication regime.

Conclusion

In this paper, by dispersion engineering and investigating the effect of dimensions on the dispersion profile, two silicon waveguides are proposed to generation of supercontinuum spectrum and frequency combs based on supercontinuum spectrum. For SCG, the pump pulse with peak power 800 (w) and pulse duration of 50 (fs) is injected to the input of both waveguides with a length of 0.8 (mm). The first zero dispersion wavelengths located near the 1980 (nm) and 1890 (nm) in the waveguides 1 and 2 respectively. However, to investigate the frequency comb generation characteristics of the waveguides, an input pulse with a pulse duration of 100 (fs) is applied in the normal dispersion region of both waveguides at the wavelength of 1550 (nm). The supercontinuum spectrum in waveguide 1 and 2 has been achieved from the wavelength of 1100 - 4000 (nm), and 1200 - 3800 (nm) respectively. The generated optical frequency combs also have a wide bandwidth and can cover the optical communication area. The proposed structures can be used in optically integrated circuits, optical communications and spectroscopy.

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