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Wavelength-assignable 1310/1550 nm wavelength conversion using completely phase-matched two-pump four-wave mixing in a silicon waveguide

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ABSTRACT

A wavelength converter between 1310 and 1550 nm bands is presented based on two-pump four-wave mixing (FWM) in a silicon waveguide. The principle of the inter-band wavelength conversion is analyzed. For an arbitrary incident signal, the converted idler wavelength can be freely assigned by suitably setting the two pump wavelengths to completely satisfy the phase-matching condition. Simulation results show that the signal can be flexibly converted between 1310 and 1550 bands. The conversion efficiencies for the signals with different wavelengths are very stable because the FWM phase-matching condition is completely met. Using this two-pump FWM configuration, channel-selective function can also be realized for wavelength division multiplexing (WDM) signals by engineering the dispersion profile of the silicon waveguide according to the WDM channel spacing.

1. Introduction

Wavelength conversion is one of the essential all-optical signal processing operations in next generation wavelength-routing optical communication networks. Since a number of access-metro schemes utilizing simultaneously 1310 and 1550 nm transmission windows have been proposed [1], the data stream has to be translated all-optically between 1310 and 1550 nm wavelength domains to ensure the system functions. This kind of inter-band wavelength conversion has attracted considerable attentions and the challenge is that the wavelength difference is quite large, which is more than 200 nm. Some methods have been developed to solve this problem. 1310 nm signals have been converted to 1550 nm using nonlinear polarization rotation in semiconductor optical amplifiers (SOAs) [2] or using cross-absorption modulation in 1550 nm electroabsorption modulators (EAMs) [3]. However, the duplex function cannot be realized using these schemes and 1550 nm signals can not be converted to 1310 nm simultaneously. Four-wave mixing (FWM) is widely considered as a promising solution to wavelength conversion due to its high speed and strict transparency. Moreover, FWM-based wavelength conversion can solve the duplex problem due to the inherent characteristics. In particular, nondegenerate FWM using two pumps shows more flexibility in phase matching and has more possibility to acquire broad conversion bandwidth, which refers to the wavelength region whose conversion efficiency drops less than 3 dB. Two-pump FWM has been well investigated in optical fibers to realize wavelength exchange [4,5] and wavelength conversion with channel selection [6], with low noise [7], or with large wavelength shift [8]. Above contributions mainly focused on the 1550 nm band. A wavelength converter from 1550 nm to 1310 nm has also been presented using two-pump FWM in a highly nonlinear photonic crystal fiber [9].

Recently, silicon emerges as an exciting FWM medium for integrated wavelength conversion due to its strong light confinement and high nonlinear coefficient. Silicon-based wavelength conversion overcomes the shortcoming of large volume in optical fibers and has the potential to realize ultra-high integration. For the wavelength conversion using FWM in silicon waveguides, the difficulty is still the realization of a conversion bandwidth more than 200 nm. Generally, there are two ways to enhance the conversion bandwidth. One effective way is to engineer the dispersion of the silicon waveguide by optimizing the waveguide geometries [10–16] or designing waveguide structures [17–20]. Some optimizations of waveguide geometries have been reported and the bandwidth has been enhanced up to more than 200 nm

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successfully by flatting the dispersion curve of the silicon waveguide [10–14]. Also, a bandwidth of more than 800 nm with an efficiency fluctuation of less than 10 dB in a dispersion-optimized silicon waveguide has been experimentally demonstrated [15]. Some special waveguide structures such as silicon nanocrystal slot waveguides [17], silicon waveguides with conformal dielectric overlayers [18], and width-modulated silicon waveguides [19, 20] have been designed to engineer the dispersion for broad wavelength conversion. These methods make high demands to the dispersion performance of the used waveguides and the waveguide fabrications for special dimension and accuracy become challengeable. The other effective way to enhance conversion bandwidth is arranging the pump wavelengths in the two-pump nondegenerate FWM regime, whose bandwidth enhancement ability has been proved theoretically and experimentally [21, 22]. In our previous work, a wavelength conversion scheme with ultrabroad bandwidth has been realized by setting one pump near the signal and scanning the other pump [23]. The bandwidth can cover the entire 1310 nm and 1550 nm bands and it is also available for the 1310/1550 nm wavelength conversion. However, the phase matching can not be completely realized in this method and the two pumps have to be set very close to the signal and the idler to reduce the phase mismatch.

In this paper, we present a 1310/1550 nm wavelength converter using two-pump FWM in a silicon waveguide under the complete phase matching. The phase-matching condition is satisfied by carefully optimizing the two pump wavelengths according to the zero-dispersion wavelength (ZDW) of the used silicon waveguide and the dispersion of the waveguide is free of careful engineering. In this kind of wavelength conversion, an arbitrary incident signal can be efficiently converted to a wavelength-assigned idler between 1310 nm and 1550 nm bands by tuning the pump wavelengths. Also, the proposed scheme has the flexibility to select and convert a channel from a series of wavelength division multiplexing (WDM) signals by adopting suitable dispersion profiles.

2. Principle

Nondegenerate FWM will occur when a signal is injected into a silicon waveguide together with two pumps. Denoting the signal and the two pump as S, P_1, and P_2, respectively, as shown in Fig. 1, the coupled equations can be expressed as follows by considering the linear loss, two-photon absorption (TPA) and TPA-induced free-carrier absorption (FCA), self-phase modulation (SPM), and cross-phase modulation (XPM) [21]

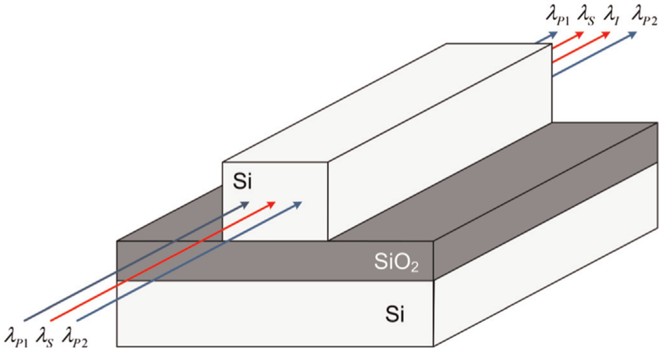

Fig. 1. Schematic description of FWM in a silicon waveguide.

$$\begin{aligned}\frac{dA_{P1}}{dz} = & -\frac{1}{2}(\alpha_{P1} + \alpha_{TPAP1} + \alpha_{FCAP1})A_{P1} \\ & + j\gamma_{P1}\left[|A_{P1}|^2 + 2|A_{P2}|^2 + 2|A_S|^2 + 2|A_I|^2\right]A_{P1} \\ & + 2j\gamma_{P1}A_S^* A_{P2} A_I \exp(j\Delta\beta z)\end{aligned} \tag{1}$$

$$\begin{aligned}\frac{dA_{P2}}{dz} = & -\frac{1}{2}(\alpha_{P2} + \alpha_{TPAP2} + \alpha_{FCAP2})A_{P2} \\ & + j\gamma_{P2}\left[2|A_{P1}|^2 + |A_{P2}|^2 + 2|A_S|^2 + 2|A_I|^2\right]A_{P2} \\ & + 2j\gamma_{P2}A_I^* A_{P1} A_S \exp(-j\Delta\beta z)\end{aligned} \tag{2}$$

$$\begin{aligned}\frac{dA_S}{dz} = & -\frac{1}{2}(\alpha_S + \alpha_{TPAS} + \alpha_{FCAS})A_S \\ & + j\gamma_S\left[2|A_{P1}|^2 + 2|A_{P2}|^2 + |A_S|^2 + 2|A_I|^2\right]A_I \\ & + 2j\gamma_S A_{P1}^* A_{P2} A_I \exp(j\Delta\beta z)\end{aligned} \tag{3}$$

$$\begin{aligned}\frac{dA_I}{dz} = & -\frac{1}{2}(\alpha_I + \alpha_{TPAI} + \alpha_{FCAI})A_I \\ & + j\gamma_I\left[2|A_{P1}|^2 + 2|A_{P2}|^2 + 2|A_S|^2 + |A_I|^2\right]A_I \\ & + 2j\gamma_I A_{P2}^* A_{P1} A_S \exp(-j\Delta\beta z)\end{aligned} \tag{4}$$

where $A_{P1,P2,S,I}(z)$ are the amplitudes of the pump, signal, and idler waves, $\gamma_{P1,P2,S,I}$ are the nonlinear coefficients, $\alpha_{P1,P2,S,I}$ are the linear-loss coefficients, $\alpha_{TPAP1,P2,S,I}$ and $\alpha_{FCAP1,P2,S,I}$ are the nonlinear-loss coefficients caused by the TPA and FCA effects. Mathematically the loss coefficient induced by TPA can be expressed as [21]

$$\alpha_{TPAi}(z) = \frac{\beta_{TPA}}{A_{eff}}\left(|A_i(z)|^2 + 2\sum_{m\neq i}|A_m(z)|^2\right), \quad (i = P1, P2, S, I;\ m = P1, P2, S, I) \tag{5}$$

$$\alpha_{FCAi}(z) = \frac{\sigma_i\beta_{TPA}\tau}{A_{eff}^2}\left(\sum_m \frac{|A_m(z)|^4}{2hf_m} + 2\sum_{m\neq n}\frac{|A_m(z)|^2|A_n(z)|^2}{hf_m + hf_n}\right) \quad (i = P1, P2, S, I;\ m = P1, P2, S, I;\ n = P1, P2, S, I) \tag{6}$$

where $f_{P1,P2,S,I}$ are the frequency of the interaction waves, β_{TPA} is the TPA coefficient, A_{eff} is the effective mode area, $\sigma_{P1,P2,S,I}$ are the FCA cross sections, τ is the effective free-carrier lifetime, and h is the Planck's constant.

Denoting the nonlinear index coefficient of silicon as n_2, the nonlinear coefficients for the involved waves can be calculated as

$$\gamma_i = 2\pi n_2 f_i / cA_{eff}, \ (i = P1, P2, S, I) \tag{7}$$

For a 1310/1550 nm wavelength converter, the information modulated on the phase and amplitude of the signal S in the 1550 nm (or 1310 nm) band need to be translated to the conjugate idler I in the 1310 nm (or 1550 nm) band. As shown in Fig. 2, this function involves two cases: convert a signal from 1550 nm to 1310 nm [see Fig. 2(a)] and from 1310 nm to 1550 nm [see Fig. 2(b)]. According to the energy conservation law, the signal, idler, and pump waves satisfy the relationship $f_{P1} - f_{P2} = f_I - f_S$, where $f_{P1,P2,S,I}$ are the frequencies of these waves. Therefore, once the incident signal frequency is fixed, one can set the two pump frequencies to generate the conjugate idler at an arbitrary frequency. However, the phase-matching condition of the FWM process has to be satisfied to ensure the conversion efficiency of the conjugate idler. In the proposed scheme, the linear phase mismatch is written as