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Modulation instability in silicon optical waveguide considering linear loss

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ABSTRACT

Taking into account the linear loss of silicon-on-insulator (SOI) waveguide, modulation instability (MI) induced by combined effects of self-phase modulation and waveguide dispersions is investigated. The impacts of various parameters to gain spectra of MI are analyzed theoretically, and direct numerical simulation of nonlinear Schroedinger equation is performed as well. Results show that strong MI takes place even in the existence of low light power. The linear loss of waveguide obviously impacts gain spectra of MI, even within ultra-short propagation distance. The peak gain frequency and bandwidth of gain spectra decrease to 41.683% and 41.6879% of their maximum at propagation distance $z = 5$ mm, respectively.

1. Introduction

Over the last few years, SOI waveguide has become an attractive investigation area because of distinct advantages such as a seamless integration with CMOS technology and high refractive index contrast, which leads to strong light confinement [1–5]. Modulation instability is a universal phenomena in which tiny phase and amplitude perturbations that are always present in a wide input beam grow exponentially during propagation due to interplay between diffraction (in spatial domain) or dispersion (in temporal domain) and nonlinearity [6–8]. For the same optical power, modulation instability effect in SOI is much stronger than that in an optical fiber, because the nonlinear parameters, which determine the strength of MI gain, are much larger for SOI waveguides as compared with that of optical fibers [8–10]. Thereby, it is significant to study the modulation instability in SOI waveguide. Nicolae et al. reported a strong modulation instability induced by co-propagating optical waves in SOI nano-wires with low optical power (∼mw) [7]. The temporal modulation instability of spatial discrete solitons in SOI waveguide arrays was studied in [11]. The linear loss of waveguide, however, is neglected in all previous literature, which obviously impacts the gain spectra of MI, even within ultra-short propagation distance.

In this paper, we investigate the modulation instability occurs in SOI waveguide, considering linear loss besides combined effects of GVD, third-order dispersion (TOD) and SPM of SOI waveguide. Simulation results indicate that strong MI can be observed in SOI sub-micrometer waveguide, even the peak light power of pulse is no more than 20 mw. Moreover, the linear loss of waveguide obviously impacts gain spectra of MI.

2. Theoretical model

In general, the dynamics of light pulse propagating in SOI waveguide is governed by modified nonlinear Schroedinger equation, which can be written as [12]:

$$\frac{\partial A}{\partial z} + i\frac{1}{2}\beta_2\frac{\partial^2 A}{\partial T^2} - \frac{1}{6}\beta_3\frac{\partial^3 A}{\partial T^3} = -\frac{1}{2}\alpha A - \frac{1}{2}\alpha_{FC}A - \frac{1}{2}\frac{\beta_{TPA}}{A_{eff}}\left|A\right|^2 A + i\gamma_{SPM}\left|A\right|^2 A + i\frac{2\pi}{\lambda}\Delta n A \quad (1)$$

where A is slowly varying amplitude of light pulse, z is transmission distance. The parameters β_2 and β_3 represent group velocity dispersion (GVD) and third-order dispersion (TOD), respectively. α is linear loss coefficient and β_{TPA} is two-photon absorption (TPA) coefficient. Parameters γ_{SPM} and γ_{Aeff} stand for self-phase modulation coefficient and modal effective area, respectively.

Considering light pulse with low peak power, the effects of TPA and FCA can be ignored. So, Eq. (1) is simplified as:

$$\frac{\partial A}{\partial z} + i\frac{1}{2}\beta_2\frac{\partial^2 A}{\partial T^2} - \frac{1}{6}\beta_3\frac{\partial^3 A}{\partial T^3} = -\frac{1}{2}\alpha A + i\gamma_{SPM}\left|A\right|^2 A \quad (2)$$

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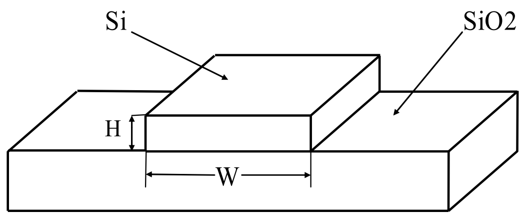

Fig. 1. Schematic diagram of silicon photonic wire.

Introducing variable substitution $u = \exp(\alpha/2z)A$, we can get the normalized Schrődinger equation:

$$\frac{\partial u}{\partial z} + i\frac{1}{2}\beta_2\frac{\partial^2 u}{\partial T^2} - \frac{1}{6}\beta_3\frac{\partial^3 u}{\partial T^3} = i\gamma_{SPM}|u|^2\exp(-\alpha z)u \quad (3)$$

When considering the case of continuous wave (CW) radiation, the amplitude A is independent of T at the input end of waveguide at $z = 0$. Assuming that A remains time independent during propagating inside waveguide, Eq. (3) is readily solved to obtain the steady-state (cw) solution:

$$u = u_0\exp\{i\gamma_{SPM}P_0\int_0^z \exp(-\alpha x)dx\} \quad (4)$$

where $P_0 = |u_0|^2$ and u_0 are initial peak power and amplitude of input pulse, respectively. To study MI, we consider a weak plane-wave perturbation of steady-state solution:

$$u = (u_0 + a)\exp\{\int_0^z i\gamma_{SPM}P_0\exp(-\alpha x)dx\} \quad (5)$$

where $a(z, T)$ is a small plane-wave perturbation, which satisfies $|a|^2 \ll P_0$. Substituting function (5) into Eq. (3) and neglecting the higher-order terms in a, we can obtain the linearized equation as:

$$\frac{\partial a}{\partial z} + i\frac{1}{2}\beta_2\frac{\partial^2 a}{\partial T^2} - \frac{1}{6}\beta_3\frac{\partial^3 a}{\partial T^3} = iP_0\exp(-\alpha z)\gamma_{SPM}(a + a^*) \quad (6)$$

where a^* stands for the complex conjugate of a. We consider the weak perturbation in the form:

$$a(z, T) = U_0\cos(K(z)z - \Omega T) + iV_0\sin(K(z)z - \Omega T) \quad (7)$$

where $K(z)$ and Ω are wave number and angular frequency of weak perturbation wave, respectively. Substituting Eq. (7) to Eq. (6) provides a set of two coupled equations for U_0 and V_0:

$$\begin{array}{l} \left[-K - \frac{dK}{dz}z + \frac{\beta_3}{6}\Omega^3\right]U_0 + \frac{\beta_2\Omega^2}{2}V_0 = 0 \\ \left[-\frac{\beta_2}{2}\Omega^2 - 2P_0\gamma_{SPM}\exp(-\alpha z)\right]U_0 + \left[K - \frac{\beta_3}{6}\Omega^3 + \frac{dK}{dz}z\right]V_0 = 0 \end{array} \quad (8)$$

Neglecting the high-order terms in (dK/dz), this set has nontrivial solution only when following dispersion relation is satisfied.

$$K(z) = \frac{\beta_3}{6}\Omega^3 \pm \frac{1}{2}[4\beta_2P_0\gamma_{SPM}\exp(-\alpha z)\Omega^2 + \beta_2^2\Omega^4]^{1/2} \quad (9)$$

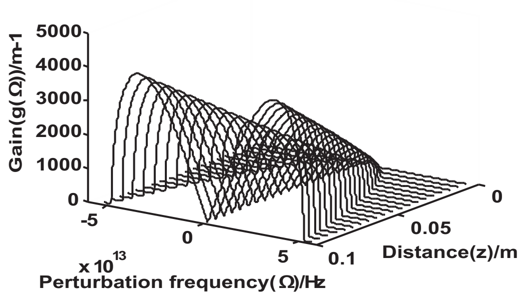

Fig. 2. Calculated gain spectra for $z = 0.005$ m when the peak power varies from 2 mw to 100 mw.

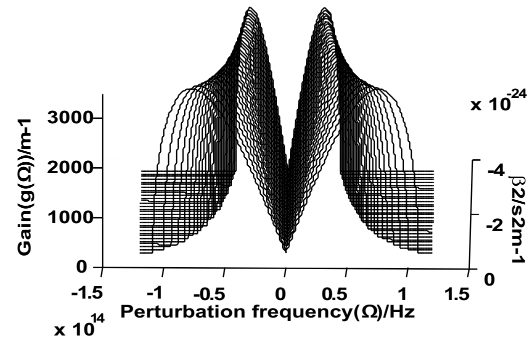

Fig. 3. The gain spectra of MI dependence when GVD varies from $\beta_2 = -0.56\,\text{ps}^2\,\text{m}^{-1}$ to $\beta_2 = -3.56\,\text{ps}^2\,\text{m}^{-1}$, with $z = 0.005$ m, $\alpha = 3.5$ dB/cm, $P_0 = 80$ mw, $\gamma_{SPM} = 3.09\text{e}4\text{w}^{-1}\,\text{m}^{-1}$.

It is obviously to see that the modulation instability occurs only when following two conditions are both satisfied, i.e., $\beta_2 < 0$ (modulation instability occurs only in anomalous regime) and $4\left|\beta_2\right|P_0\gamma_{SPM}\exp(\alpha z)\Omega^2 - \beta_2^2\exp(2\alpha z)\Omega^4 \geq 0$. The corresponding gain spectra of MI can be written as:

$$g(\Omega) = 2Im(K) = [4\left|\beta_2\right|P_0\gamma_{SPM}\exp(-\alpha z)\Omega^2 - \beta_2^2\Omega^4]^{1/2} \quad (10)$$

It is well known that the gain of MI is independent of TOD parameter, which agrees with the result obtained in fiber [13].

3. Analysis and discussion

3.1. The impact of P_0 to MI gain spectra

We consider a silicon wire with cross-section diagram as Fig. 1 and corresponding configuration parameters as $W = 0.36\,\mu$m, $H = 0.22\,\mu$m. Other parameters used in simulations are $\alpha = 3.5$ dB/cm, $\beta_2 = -3.14\,\text{ps}^2/\text{m}$ and $\gamma_{SPM} = 3.09 \times 10^4 w^{-1}m^{-1}$ [9]. Simulation result in Fig. 2 shows that the propagation wave experiences strong MI when peak power P_0 varies from 2 mw to 100 mw. Note that the MI gain is $\sim 10^2$ times as larger as that achievable in optical fibers, for similar values of the optical power P_0 [14]. This is because the susceptibility $\hat{x}^{(3)}$ of Si is much larger than that of silica, whereas the modal area of SOI waveguide is much smaller than that of optical fibers [7]. As a result, the nonlinear parameter which determine the strength of MI, are much larger for SOI waveguide as compared with that of optical fibers. Moreover, the peak gain, bandwidth and peak gain frequency of gain spectra increase with the growth of peak power of pulse, because the higher peak power P_0 induces stronger nonlinear effect, and results in stronger MI.

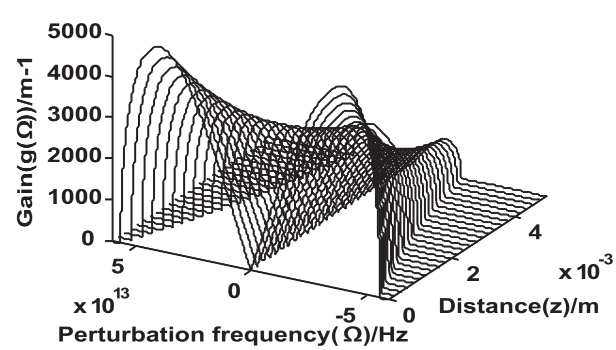

Fig. 4. Gain spectra of MI occurred in a silicon photonic wire with linear loss coefficient $P_0 = 80$ mw and $\alpha = 3.5$ dB/cm.