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Analysis of difference frequency generation and cascaded second-harmonic generation and difference frequency generation in lossy quasi-phase-matched semiconductor waveguides

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ABSTRACT

The analytical expressions of converted wave power for difference frequency generation (DFG), cascaded second-harmonic generation and difference frequency generation (cSHG/DFG) processes have been obtained under the non-depletion approximation in lossy waveguides. It is shown that the analytical results and the numerical simulation with depletion agree very well for lossy waveguides. Employing the analytical solutions, the formulas of optimized waveguide lengths in lossy waveguides are obtained for DFG and cSHG/DFG processes. After designing an AlGaAs quasi-phase-matched ridge waveguide, we investigate and compare the characteristics of the second-order nonlinear effects with and without waveguide loss, such as conversion efficiency, conversion bandwidth, pump wavelength tolerance and temperature stability in detail.

1. Introduction

Wavelength division multiplexed (WDM) systems offer high capacity by effectively utilizing the optical fiber bandwidth. In WDM optical networks, an important technique is wavelength conversion [1]. The difference frequency generation (DFG), one of the second-order nonlinear optical interactions for wavelength conversion, has attracted considerable interest with some advantages (i.e., low noise, strict transparency, broad conversion bandwidth and simultaneous multichannel conversion ability [2–4]). However, the wavelength of pump wave for DFG process is far away from the widely used 1.55 μm band in optical fiber communication systems. In order to develop the wavelength conversion with 1.55-μm band pump, many research groups have adopted the cascaded second-order nonlinear optical effects, such as cascaded second-harmonic generation and difference frequency generation (cSHG/DFG) [5] and cascaded sum-frequency generation and difference frequency generation (cSFG/DFG) [6–11], where wavelength conversion is conveniently achieved by overcoming the difficulty in coupling the pump and the signal waves into the fundamental mode of the fibers and waveguides.

For efficient wavelength conversion, the nonlinear material and the phase-matched condition are two essential items. The AlGaAs, compound III–V semiconductor alloy, is a very attractive material because of its high quadratic nonlinearity. Due to the optical isotropy of cubic semiconductor crystals, birefringent phase matching (BPM) has not been realized in conventional semiconductor waveguide. A sublattice-reversal epitaxial growth technique has been applied to the fabrication of orientation-patterned AlGaAs for quasi-phase-matched (QPM) wavelength conversion devices [12–16]. Other phase matched techniques, such as form-birefringence phase matching (FBPM) [17,18], modal phase matching (MPM) [19], and Bragg reflection waveguide phase matching [20,21], to realize wavelength conversion have been reported. Unfortunately, the efficient nonlinear waveguide devices based on AlGaAs system have to confront the large propagation loss at either the pump or signal wavelength. In lossless or low-loss waveguides, the generated output power and the normalized conversion efficiency are approximately proportional to the square of the waveguide length for undepleted pumps [22–24]. In large lossy waveguides, the attenuation of the waves results in most of the converted wave power which is generated close to the output end exiting the waveguide. The maximum conversion efficiency may be obtained with an optimized waveguide length that depends on the loss at all wavelengths. Therefore it is necessary to investigate the influence of the loss on second-order nonlinear wavelength conversion and calculate the optimized length before the fabrication of the optical waveguides.

In this paper, we study the DFG and cSHG/DFG processes in a lossy QPM AlGaAs waveguide using the analytical method and

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numerical method. The analytical solution of converted wave powers for DFG and cSHG/DFG processes is derived from the coupled-mode equations under the non-depletion approximation. The numerical simulation is based on the step-changed finite difference method for the depletion situation. It is shown that the analytical method fit the numerical method very well for our model. Employing the analytical solution, the formulas of optimized waveguide lengths in lossy waveguides are obtained for DFG and cSHG/DFG processes. The nonlinear properties of the ridge AlGaAs waveguide include the conversion efficiency, conversion bandwidth, pump wavelength tolerance and temperature stability, are also analyzed.

2. Principle and theoretical model

A schematic representation of the nonlinear DFG and cSHG/DFG interactions is depicted in Fig. 1. In the DFG process, input signal (ω_S) and the pump wave (ω_P) generate a new idler wave ($\omega_i=\omega_P-\omega_S$). For optical fiber communication applications, the signal and idler wavelengths are in 1.55 μm band, and the pump is near 0.77 μm. The large difference between signal and pump wavelengths causes difficulties in coupling light into the waveguide. The single mode condition of the 0.77 μm band may hardly be satisfied if fiber is used in the coupling. In the cSHG/DFG process, pump wave (ω_P) is used to yield a second-harmonic wave with doubled frequency ($\omega_{SH}=2\omega_P$) through the SHG process. At the same time, the signal wave (ω_S) interacts with the second-harmonic wave to generate an idler wave ($\omega_i=2\omega_P-\omega_S$). In this case, both the pump and signal wavelengths are in the wavelength range of 1.55 μm, so they can easily be kept in single mode if fibers are used in the coupling.

The model considers second-order nonlinear interactions propagating in a lossy waveguide. We assume that the optical waves in the waveguide can be treated as propagating along z-axis. Thus the electric fields of different optical waves can be expressed as

$$E_j(x,y,z,t)=\tfrac{1}{2}e_j(x,y)E_j(z,t)\exp(\mathrm{i}k_jz-\mathrm{i}\omega_jt)+c.c., \tag{1}$$

where $j=S,P,SH,i$ refer to the signal, pump, second-harmonic wave and idler wave, respectively. $e_j(x,y)$ is the normalized transverse field profile and is defined by

$$\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} e_j^2(x,y)\,\mathrm{d}x\,\mathrm{d}y=1. \tag{2}$$

$E_j(z,t)$ is the complex amplitude of electric field. k_j is the propagation constant at frequency ω_j. Due to the strong field confinement in waveguides, the $E_j(z,t)$ can be normalized as

$$A_j(z,t)=\sqrt{\frac{S_jn_j}{2c\mu_0}}E_j(z,t), \tag{3}$$

where n_j is the effective refractive index, μ_0 is the permeability of free space, and c is the light velocity in vacuum. The S_j is the effective mode field area, and can be expressed as

$$S_j=\frac{\left(\int\int|e_j(x,y)|^2\,\mathrm{d}x\,\mathrm{d}y\right)^2}{\int\int|e_j(x,y)|^4\,\mathrm{d}x\,\mathrm{d}y}. \tag{4}$$

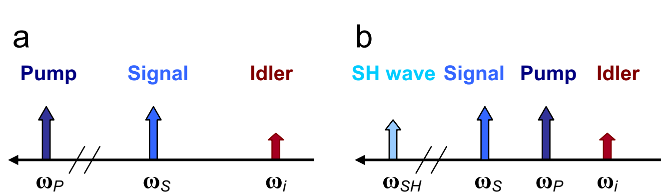

Fig. 1. Scheme of second-order nonlinear interactions. (a) DFG. (b) cSHG/DFG.

Note that such normalization yields the optical power as

$$|A_j(z,t)|^2=P_j=\frac{1}{2}n_j\sqrt{\frac{\mu_0}{\varepsilon_0}}|E_j(z,t)|^2S_j, \tag{5}$$

where ε_0 is the permittivity of free space.

Under the slowly varying envelope approximation, where the electric field amplitude changes slowly relative to the fast optical carrier frequency, we can derive the following coupled-mode equations for DFG and cSHG/DFG processes respectively [25].

$$\begin{aligned}
&\frac{\partial A_P}{\partial z}+\frac{1}{2}\alpha_PA_P=\mathrm{i}\omega_p\kappa_{DFG1}A_SA_i\exp(-\mathrm{i}\Delta k_{DFG1}z),\\
&\frac{\partial A_S}{\partial z}+\frac{1}{2}\alpha_SA_S=\mathrm{i}\omega_S\kappa_{DFG1}A_i^*A_P\exp(\mathrm{i}\Delta k_{DFG1}z),\\
&\frac{\partial A_i}{\partial z}+\frac{1}{2}\alpha_iA_i=\mathrm{i}\omega_i\kappa_{DFG1}A_S^*A_P\exp(\mathrm{i}\Delta k_{DFG1}z),
\end{aligned} \tag{6}$$

and

$$\begin{aligned}
&\frac{\partial A_P}{\partial z}+\frac{1}{2}\alpha_PA_P=\mathrm{i}\omega_p\kappa_{SHG}A_S^*A_{SH}\exp(\mathrm{i}\Delta k_{SHG}z),\\
&\frac{\partial A_{SH}}{\partial z}+\frac{1}{2}\alpha_{SH}A_{SH}=\frac{\mathrm{i}}{2}\omega_{SH}\kappa_{SHG}A_PA_P\exp(-\mathrm{i}\Delta k_{SHG}z)\\
&\qquad\qquad+\mathrm{i}\omega_{SH}\kappa_{DFG2}A_SA_i\exp(-\mathrm{i}\Delta k_{DFG2}z),\\
&\frac{\partial A_S}{\partial z}+\frac{1}{2}\alpha_SA_S=\mathrm{i}\omega_S\kappa_{DFG2}A_i^*A_{SH}\exp(\mathrm{i}\Delta k_{DFG2}z),\\
&\frac{\partial A_i}{\partial z}+\frac{1}{2}\alpha_iA_i=\mathrm{i}\omega_i\kappa_{DFG2}A_S^*A_{SH}\exp(\mathrm{i}\Delta k_{DFG2}z),
\end{aligned} \tag{7}$$

where for a QPM waveguide

$$\begin{aligned}
&\kappa_{DFG1}=d_{eff}\sqrt{\frac{2\mu_0}{cn_Pn_Sn_iA_{eff}}},\\
&\kappa_{SHG}=d_{eff}\sqrt{\frac{2\mu_0}{cn_Pn_Pn_{SH}A_{eff}}},\\
&\kappa_{DFG2}=d_{eff}\sqrt{\frac{2\mu_0}{cn_{SH}n_Sn_iA_{eff}}},\\
&\Delta k_{DFG1}=k_P-k_S-k_i-\frac{2\pi}{\Lambda},\\
&\Delta k_{SHG}=k_{SH}-2k_P-\frac{2\pi}{\Lambda},\\
&\Delta k_{DFG2}=k_{SH}-k_S-k_i-\frac{2\pi}{\Lambda}.
\end{aligned} \tag{8}$$

In the above equations, A_S, A_P, A_{SH} and A_i, as functions of the position z and time t, denote the normalized complex amplitudes of the signal, pump, second-harmonic wave and idler wave respectively. $\alpha_j(j=S,P,SH,i)$ is the waveguide propagation loss coefficient. κ_{DFG1} and Δk_{DFG1} respectively refer to the DFG coupling coefficient and DFG phase mismatching. κ_{SHG}, κ_{DFG2}, Δk_{SHG} and Δk_{DFG2} represent the corresponding coefficients for cSHG/DFG. $d_{eff}=(2/\pi)d$ is the effective nonlinear coefficient for first-order QPM waveguides, and nonlinear coefficient d depends on the crystal material and the polarization of optical waves. Λ is the period of the periodically poled structure in the waveguide. The A_{eff} is the effective nonlinear interaction area, and for DFG process