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Efficient frequency conversion by amplitude modulation

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ABSTRACT

An efficient wavelength conversion scheme based on amplitude modulation is proposed, and it demonstrated by mathematical formulate in an MgO-doped $LiNbO_3$ quasi-phase-matched waveguide. This method is based on the adiabatic physical process of two-state systems. By nonlinear modulate the overlap of waveguide modes to achieve the purposes of phase-matching and modulate the coupling coefficient. Under the adiabatic constraints condition, we simulate numerically difference frequency generation process. The results shown that this scheme can lead to almost complete transfer of energy from near-IR (~1064 nm) to mid-IR (~3.53 μm) in a stable manner. Furthermore, we also present two analytically exactly soluble models, in which the coupling coefficient is a linear function of propagation distance and the phase mismatch is a constant.

1. Introduction

Mid-IR lasers in the 3–5 μm wavelength region have many applications, such as military countermeasures, remote monitors of the special environment, spectrum, and so on [1,2]. For the generation of infrared (IR) radiation, parametric generation is the simplest approach [3,4]. However, the requirements of phase matching are critical to high frequency conversion. Especially for the ultrashort pulses generation, conversion bandwidth and the conversion efficiency often cannot be satisfied at the same time [5,6]. Therefore, exploring broadband and efficient frequency conversion methods is a meaningful thing.

In recent years, by analogizing to the frequency transformation process with a two-level atom system dynamics, the concept of adiabatic frequency conversion has been proposed [7,8]. It has been shown that nonlinear interactions in chirped QPM gratings can exhibit high efficiencies due to an adiabatic following process. But this behavior occurs for interactions that are both plane-wave and monochromatic, provided QPM grating is sufficiently chirped.

In this paper, a technique called mode-overlap control (MOC) [9,10] be employed to modulate the coupling coefficient, we also obtain high conversion efficiency. This feat is accomplished in a manner analogous to population transfer in atomic rapid adiabatic passage (RAP) [11,12]. In addition, we also present two analytically exactly soluble models, in which the coupling coefficient is a linear function of propagation distance and the phase mismatch is a constant. As it shows that modulate the coupling coefficient can also achieved high efficiency signal-to-idler conversion.

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2. Theoretical model and analysis

Suppose a rather general model of pump and signal wave in a transversely patterned QPM grating. The electric field at the frequency ω_m is $E_m = u_m(x,y)e_m(z)\exp i(\omega_m t - k_m z) + c.c$, $u_m(x,\ y)$ $(m=1,\ 2,\ 3)$ is the normalized mode profile at frequency of $\omega_m(\iint |u_m(x,y)|^2 dxdy = 1)$, $k_m = (\omega_m n_m / c_0)$ is propagation constant, where n_m is the refractive index, the nonlinear coupling equations [13] for the field amplitudes e_m is

$$\frac{de_1}{dz} = -2i\frac{\omega_1 d_{\text{eff}}}{n_1 c}\kappa^*(z)e_2 e_3 \tag{2 – 1a}$$

$$\frac{de_2}{dz} = -2i\frac{\omega_2 d_{\text{eff}}}{n_2 c}\kappa(z)e_1 e_3{}^* \tag{2 – 1b}$$

$$\frac{de_3}{dz} = -2i\frac{\omega_3 d_{\text{eff}}}{n_3 c}\kappa(z)e_2{}^* e_1 \tag{2 – 1c}$$

Coupling coefficient $\kappa(z) = \exp(-i\Delta kz)(\iint dxdyu_1 u_2 u_3)d(x,y,z)$, different frequency $\omega_3 = \omega_1 - \omega_2$, the phase mismatch $\Delta k = k_1 - k_2 - k_3$, $d(x,y,z)$ defines the spatially dependent sign of the nonlinear interaction ($d=1$ in positive domains, $d=-1$ in inverted domains).

The coupled nonlinear Eq. (2–1a–c) are often linearized, assuming that the incident signal field is much stronger than other fields and therefore its amplitude is nearly constant (undepleted) during the evolution. In this paper, we assume the "pump" is the middle frequency wave ω_2, where as the "signal" is the high-frequency wave ω_1 and the "idler" is the low-frequency wave ω_3. Then Eq. (2–1a–c) are reduced to a system of two linear equations [14]

$$id|\varphi\rangle/dz = H|\varphi\rangle,\ H = \begin{bmatrix} -\Delta k/2 & |\kappa| \\ |\kappa^*| & \Delta k/2 \end{bmatrix} \quad (2-2)$$

where $|\varphi\rangle\Big| = [\varphi_1, \varphi_3]^T$, $\varphi_1 = \frac{ce_1}{4\omega_1}\sqrt{\frac{k_1}{2\pi d_{eff} e_2}}\exp(i\Delta kz/2)$, $\varphi_3 = \frac{ce_3}{4\omega_3}\sqrt{\frac{k_3}{2\pi d_{eff} e_2}}\exp(-i\Delta kz/2)$, $\kappa(z) = 2\pi\omega_1\omega_3 d_{\text{eff}}/\sqrt{k_1 k_3}c^2$. Upon the substitution $z \to t$, Eq. (2-2) has the same form of the time-dependent Schrödinger equation for a two-state quantum system. Following the approach of Suchowski et al. [7,8], the time evolution is replaced by propagation in z-axis and the resonance parameter Δ is replaced by the phase-mismatch Δk value, Rabi frequency $\Omega(t)$ is replaced by coupling parameters $\kappa(z)$, the population of the ground and excited states are analogous to the magnitude of the input and output fields, respectively. In two-state coherent population systems, if have the pulsed interaction, the adiabatic energies will be a superposition of diabatic states at intermediate times and have adiabatic follows process [15]. We are going to use the adiabatic follows process in frequency conversion.

The two eigenvalues of the coupling matrix H are [14]

$$\lambda_1 = -\sqrt{(\Delta k/2)^2 + \kappa^2},\ \lambda_3 = \sqrt{(\Delta k/2)^2 + \kappa^2} \quad (2-3)$$

Defining $\tan(2\theta) = 2|\kappa|/\Delta k(z)$; according to the two level systems in atomic physics [16,17], the adiabatic dressed fields is $\varphi_1^{'} = -\cos(\theta)\varphi_1 + \sin(\theta)\varphi_3$, $\varphi_3^{'} = \sin(\theta)\varphi_1 + \cos(\theta)\varphi_3$. If the system is at an eigenstate and is subject only to adiabatic changes, it will remain at the same eigenstate. When the mixing angle θ rotates from 0 to $\pi/2$, all power will be completely transferred from φ_1 to φ_3. In order to ensure the θ adiabatic changes, the coupling between the dressed fields must be negligible compared with the difference between their eigenvalues

$$\left|\left\langle \frac{d}{dz}\varphi_1^{'} \middle| \varphi_3^{'} \right\rangle\right| \ll |\lambda_1 - \lambda_3| \quad (2-4)$$

Defining the parameter $r = \frac{1}{|\lambda_1 - \lambda_3|}\left|\left\langle \frac{d}{dz}\varphi_1^{'} \middle| \varphi_3^{'} \right\rangle\right|$, we could obtain the adiabatic criterion of frequency conversion

$$r = \frac{|\Delta k(z)|}{2(\Delta k^2 + |\kappa|^2)^{3/2}} \times \left|\frac{d\kappa(z)}{dz}\right| \ll 1 \quad (2-5)$$

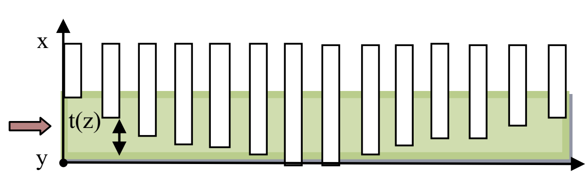

Fig. 1. The transverse patterning of the grating, with domain reversal at the shaded regions corresponding to $d(x,y,z) = -1$, provides mode-overlap control and tailoring of the coupling terms.

Furthermore, for the purpose of satisfying simultaneously phase match and independently control their interaction strength, we consider the transverse patterning [9,10] of $d(x,y,z)$ shown in Fig. 1

With the gratings patterned into and out of the waveguide, the overlap of the waveguide mode will nonlinearity modulated, this method is called mode-overlap control (MOC) [9,10]. Introduce the overlap integrals $f(t) = \int_{-\infty}^{t(z)} dx \int_{-\infty}^{+\infty} dy u_1 u_2 u_3(x,y)$, the coupling parameters slowly varying given by the local averaged values of κ, and the coupling coefficient expression is

$$\kappa_1(z) = \frac{2}{\pi} f[t(z)]\ \sin(\pi D)\exp\left[-i(\Delta k \pm 2\pi/\Lambda)z\right] \quad (2-6)$$

3. Numerical simulation under ideal conditions

The design was carried out by numerical simulation of the Eq. (2-1a–c) using the variable-step fourth-order Runge–Kutta method. Both pump and signal models are assumed Gaussian beams in a 50-mm long periodically PPLN waveguide which satisfies the constraints posed by Eq. (2-4). For the sake of simplicity, assume $u_m(x,y) = \sqrt{2/\pi}(1/w_m)\exp[-(x^2+y^2)/w_m^2]$, and $w_1 = w_3 = 1$ mm, $w_2 = 50$ µm. The $t(z)$ is a quadratic equation, $t(z) = 2.5 \times 10^{-3} \times (2z/L-1)^2$. The pump and signal light wavelength are 1523 nm and 1064 nm, respectively. Difference frequency generation idler light is 3.53 µm, and the other structural parameters can be calculated from the Sellmeier equation [18]. The pump intensity was set 280 MW/cm^2 and signal intensity was set 0.127 MW/cm^2. Fig. 2 Part (a) shows the normalized intensities of the interacting waves along the nonlinear crystal. If every photon at λ_1 is converted to a photon at λ_3, the intensity ratio is $I_1/I_3 = \omega_1/\omega_3 = \lambda_3/\lambda_1$, full conversion means $I_3 = 0.303$, so the input power is considered to be fully converted to the output wave. In the same condition, the conversion efficiency of constant coupling is far less than adiabatic MOC, Fig. 2 Part (b) shows the corresponding results. The conversion efficiency of constant coupling is displayed that maximum value reaches at most 5×10^{-3} far less than the adiabatic conversion efficiency in the inset.

No matter Birefringent Phase Matching (BPM) or QPM, both methods are typically very sensitive to the incoming frequency, angle, temperature or other tuning mechanisms, due to the requirement of phase matching. However, satisfied adiabatic criterion of mode-overlap control method is not restricted by $\Delta k = 0$. For comparison, we assume $\Delta k = 10$ m^{-1}, 100 m^{-1}, 200 m^{-1}, respectively, repeated the same simulation, the results are depicted in Fig. 3. As is shown in Fig. 3 Part (a), when $\Delta k < 100$ m^{-1}, conversion efficiency is more than 60 percent. Although phase matching is no longer restricted $\Delta k = 0$, Δk also cannot very large, because of achieving full of energy transfer in parameter conversion process, it not only requires adiabatic condition to be satisfied, but also

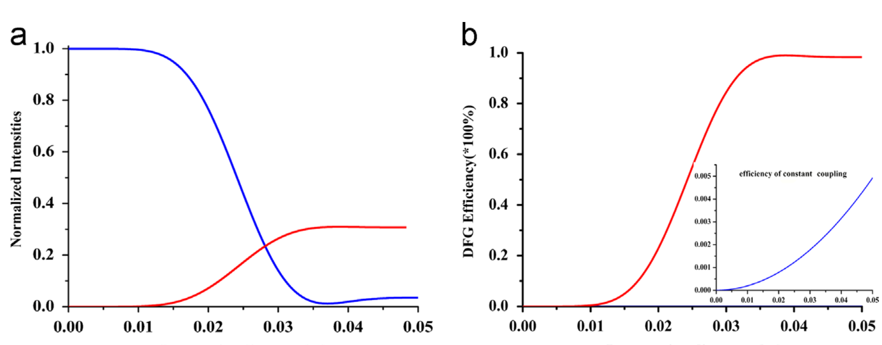

Fig. 2. Numerical simulation of the intensities of the interacting waves along the nonlinear medium in adiabatic coupling. Part (a) is normalized intensities of the interacting waves along the nonlinear crystal. Part (b) is the conversion efficiency of constant coupling and adiabatic MOC, respectively