Two-process frequency conversion under stimulated Raman adiabatic passage via a continuum of dark intermediate modes

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ABSTRACT
We study two-process frequency conversion using three wave mixing processes under stimulated Raman adiabatic passage in a planar-channel waveguide structure via an intermediate continuum of radiation modes with negligible power accumulation. The device is shown to have large bandwidth as well as high efficiency.
Keywords: Planar waveguides, Channel waveguides, Nonlinear Optics

1. INTRODUCTION

STIRAP is a simple, efficient and robust technique for population transfer under adiabatic interaction among two atomic levels via an intermediate level using two spatially overlapping laser beams referred to as pump and Stokes beams, arranged in a temporally counterintuitive fashion and during this process, the intermediate state remains unpopulated which is advantageous[1]. Recent analogy between quantum mechanical multilevel systems and optical systems has facilitated the application STIRAP into optical systems as well [2].

Three wave mixing (TWM) processes in second order nonlinear media exhibiting quasi phase matching has been widely used for optical frequency conversion to prepare new light sources. However, it is usually very difficult to generate new frequencies very near or very far from the input frequencies via a single TWM process and therefore, multistep TWM processes can be used. This generates a new problem of absorption losses at the intermediate frequency which causes degradation in efficiency for overall conversion. This problem can be resolved using the STIRAP process which prevents accumulation of any power at the intermediate frequencies.

Notwithstanding very high efficiency of the multiple TWM processes occurring simultaneously, the process is bandwidth limited because the phase matching can be satisfied for only a single set of frequencies under QPM with single period gratings. In bulk systems, in order to get the required power densities for TWM processes, large pump powers are required due to diffraction effects; however large bandwidths can be realized due to presence of continuum of propagating modes in both the transverse directions. In channel optical waveguides, light confinement in both the transverse directions leads to much lower power requirements but with the associated disadvantage of very small tunability with respect to input wavelength due to the discrete nature of the interacting modes. On the other hand, in the case of planar waveguides, the confinement is in one of the transverse directions while the light can diffract in other leading to lesser power requirement than bulk (due to the confinement) and higher tunability than channel waveguides (due to the presence of a continuum of modes in one transverse dimension). Here we propose a novel hybrid planar-channel waveguide structure to study a highly efficient as well as broadband two simultaneous TWM processes using STIRAP. The proposed waveguide geometry has a channel waveguide surrounded by a planar structure as shown in Figs. 1 (a) and (b).

2. THEORETICAL ANALYSIS

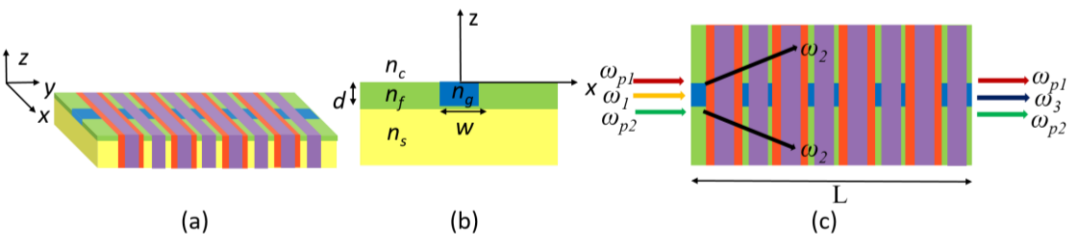

Figure 1 (a) Schematic diagram of a hybrid planar-channel waveguide configuration for a two process TWM process under STIRAP via continuum (b) The cross sectional view (c) The top view of the structure. The two pumps, input and the output frequencies propagate within the channel waveguide region with the intermediate frequency radiating in the planar region.

For the study we consider a *z*-cut and *y*-propagating periodically poled lithium niobate waveguide with channel waveguide surrounded by a planar waveguide region (see Fig. 1(a) and (b)). The two pump frequencies (pump1: ω_{p1} and pump2: ω_{p2}), the incident input at ω_1 and the output at ω_3 are assumed to be guided modes of the channel waveguide while the intermediate frequency at ω_2 is assumed to be a superposition of radiation modes of the planar waveguide. The frequency conversion efficiency depends upon the phase matching condition and it can be satisfied for both the processes simultaneously using two independent gratings under QPM. The phase matching conditions for SFG ($\omega_2 = \omega_1 + \omega_{p_1}$) and DFG ($\omega_3 = \omega_2 - \omega_{p_2}$) respectively are $\Delta\beta_1 = \beta_2 - \beta_{p_1} - \beta_1 - K_1 = 0$ and $\Delta\beta_2 = \beta_2 - \beta_{p_2} - \beta_3 - K_2 = 0$ where β_{p1}, β_{p2}, β_1 and β_3 correspond to the propagation constants of the guided modes at frequencies ω_{p1}, ω_{p2}, ω_1 and ω_3 in the channel waveguide region, $\beta_2 = \beta_{2p}\cos\theta$ with β_{2p} being the propagation constant for the mode at frequency ω_2 in the planar region ($n_c < n_s < n_f$) and $K_1 = 2\pi/\Lambda_1$ and $K_2 = 2\pi/\Lambda_2$ with Λ_1 and Λ_2 being the poling period corresponding to the two gratings used for quasi phase matching SFG and DFG processes respectively. β_2 takes continuous values due to continuum of modes in *x*-direction in the planar region and therefore, if we chose one of the radiation modes for the intermediate frequency out of the continuum, we can fix the grating periods corresponding to that radiation mode which is exactly phase matched for both the TWM processes. This also fixes the angle θ at which the peak of the generated intermediate wave propagates. Now if the input wavelengths change, then due to the continuous spectrum of β_2, there would always be some radiation mode which will satisfy the required phase matching conditions. This results in an increase in the bandwidth of the conversion process.

The equations governing the interaction of the all the five fields can be obtained by the standard coupled mode theory approach and the coupled equations describing the evolution of the input, intermediate and the output frequency under undepleted pump approximation can be derived using the standard process and the equations can be written as

$$i\frac{dA_1}{dy} = \kappa_{12}\int A_2(y,\beta_2)\gamma_1(\beta_2)e^{-i\Delta\beta_1 y}d\beta_2; i\frac{dA_2}{dy} = \kappa_{21}A_1\gamma_1^*(\beta_2)e^{i\Delta\beta_1 y} + \kappa_{23}\gamma_2^*(\beta_2)e^{i\Delta\beta_2 y}; i\frac{dA_3}{dy} = \kappa_{32}\int A_2(y,\beta_2)\gamma_2(\beta_2)e^{-i\Delta\beta_2 y}d\beta_2 \quad (1)$$

where A_{p1}, A_{p2}, A_1 and A_3 correspond to the *y*-dependent amplitudes and ψ_{p1}, ψ_{p2}, ψ_1 ,and ψ_3 correspond to the transverse modal fields of the guided modes in the channel waveguide region at ω_{p1}, ω_{p2}, ω_1 and ω_3 respectively, ψ_2 corresponds to the transverse modal field of the planar waveguide mode with a propagation constant β_2 corresponding to the intermediate frequency in the planar waveguide region and $A_2(\beta_2, y)$ is the amplitude of the mode and is a function of β_2 because of continuum of modes (continuous β_2) in *x*-direction, γ_1 and γ_2 correspond to the overlap integrals and $\kappa_{12} = 2\omega_1^2 d_{33}A_{p_1}^* / \pi c^2\beta_1$, $\kappa_{21} = 2\omega_2^2 d_{33}A_{p_1} / \pi c^2\beta_2$, $\kappa_{23} = 2\omega_2^2 d_{33}A_{p_2} / \pi c^2\beta_2$ and $\kappa_{32} = 2\omega_3^2 d_{33}A_{p_2}^* / \pi c^2\beta_3$, where d_{33} is the effective nonlinear coefficient and *c* is the velocity of light in free space. The contribution from the continuum of modes can be eliminated by following a well-known standard procedure followed in quantum mechanical systems under Markovian approximation [3]. The condition for trapped state (dark state) can be obtained through a heuristic mathematical analysis of the coupled equations and the condition required for existence of trapped states is $\gamma_1 = \gamma_2$ and complete transfer of power from input frequency to output is possible without exciting the intermediate frequency requires $\kappa_{23} \gg \kappa_{21}$ at $y = 0$ and $\kappa_{21} \gg \kappa_{23}$ at $y = L$. We will show in the next section that in the proposed configuration, almost complete transfer of power from input frequency to the output frequency, under nearly trapped state i.e. $\gamma_1 \approx \gamma_2$, is possible.

3. NUMERICAL RESULTS

In order to demonstrate the feasibility of the device structure for the two process frequency conversion under STIRAP via continuum, we have carried out the numerical simulations for a *z*-cut *y*-propagating titanium indiffused lithium niobate waveguide. For the intermediate frequency, we have used the separation of variable technique and have calculated the propagation constant for the guided modes along *z*-direction and taken the continuum of modes along *x*-direction with propagation constant value being continuous and satisfying the condition $0 < \beta_2^x < k_0 n_f$. Here β_2^x correspond to the propagation constant in *x*-direction corresponding to the continuous radiation modes in that direction in the planar region. Since β_2^x is continuous, this in turn results into continuous β_2.

For numerical simulation we have chosen the various wavelengths to be $\lambda_{p_1} = 3000$ nm, $\lambda_{p_2} = 2800$ nm, $\lambda_1 = 1500$ nm and $\lambda_3 = 1667$ nm. This results in an intermediate wavelength of $\lambda_2 = 1000$ nm. In order to optimize the device we first obtain the variation of both the overlap integrals with respect to β_2 which are shown in Fig. 2 (a). It can be seen that the two overlap integrals are very close to each other. To maximize efficiency we fix β_2 corresponding to the maximum overlap as the perfect phase matching intermediate mode.

Figure 2(b) shows the variation of power in the three generated frequencies along the length of propagation. It may be observed from Fig. 2(b) that at the output end the ratio of output power P_3 at ω_3 to the input power P_1 at ω_1 is 0.892 which is very close to the maximum conversion ratio of 0.9 for the two frequencies (equal to the ratio of the output frequency ω3 to input frequency ω1). The figure also shows that there is almost no power in the continuum modes at frequency ω2 over the entire length of interaction. Therefore, we can say that even if we deviate slightly from the completely trapped condition, almost complete conversion from input to output frequency via an intermediate is possible under STIRAP with the intermediate forming a continuum.

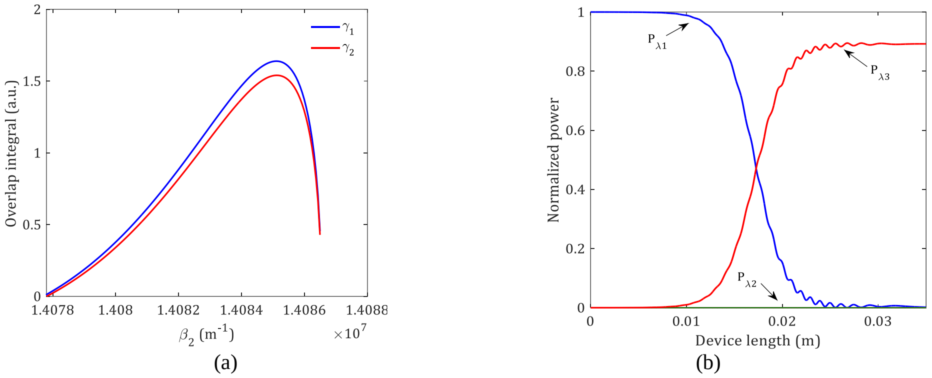

Figure 2 (a)Variation of the two overlap integrals, γ_1 and γ_2 , corresponding to SFG and DFG processes respectively with β_2 (b) Almost complete transfer of power from input frequency to output frequency is possible for almost trapped state case.

The intermediate wave propagating in the planar region forms a continuum and therefore, the two process frequency conversion under STIRAP in the proposed structure has a large tolerance with respect to the variation in the input wavelength unlike in the case of all guided configuration where all the frequencies lie within the channel waveguide. In order to demonstrate this aspect, we have simulated the variation of normalized power at the output frequency with respect to the input wavelength for our proposed hybrid planar-channel waveguide configuration in Fig. 3(a) and for the all guided configuration in Fig. 3(b). We can see from the figures that the bandwidth corresponding to the all guide wave configuration is 20 nm while for the proposed configuration it is 150 nm which is much larger.

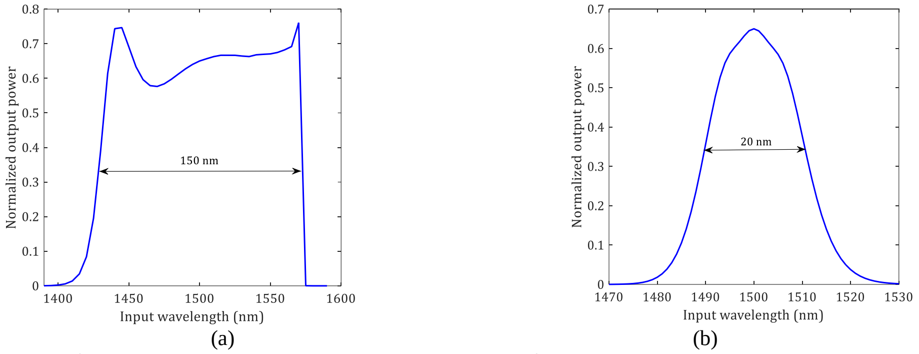

Figure 3 Variation of normalized output power with the input wavelength for the SFG-DFG process under STIRAP (a) for all guided configuration with 3 dB bandwidth of 20 nm (b) for our proposed hybrid planar-channel waveguide structure with 3 dB bandwidth of 150 nm

4. CONCLUSIONS

In conclusion, we have proposed a novel device structure with a hybrid planar-channel waveguide configuration and used the STIRAP process with the input waves and the generated frequency being guided modes and the intermediate frequency being a continuum of modes in the planar waveguide. We have shown that the proposed device has a broad bandwidth as well as high efficiency in comparison to the all guided configuration. The proposed idea can be used for the generation of new frequencies with high efficiency and large bandwidth using multiple nonlinear processes.

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