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Wave-mixing-induced transparency with zero phase shift in atomic vapors

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ABSTRACT

We present a wave-mixing induced transparency that can lead to a hyper-Raman gain-clamping effect. This new type of transparency is originated from a dynamic gain cancellation effect in a multiphoton process where a highly efficient light field of new frequency is generated and amplified. We further show that this novel dynamic gain cancellation effect not only makes the medium transparent to a probe light field at appropriate frequency but also eliminates the probe field propagation phase shift. This gain-cancellation-based induced transparency holds for many potential applications on optical communication and may lead to effective suppression of parasitic Raman/hyper-Raman noise field generated in high intensity optical fiber transmissions.

1. Introduction

The terminology of *interference* describes a class of phenomena in which the amplitudes of various physical processes influence and affect each other, resulting pronounced coherent build-up of certain fields if some amplitudes are in-phase, or complete cancellation of certain features when the amplitudes of the physical processes are 180°out-of-phase. Quantum interference effect is the foundation of quantum mechanics [1]. In fact, the effect of interference between waves was the primary reason that quantum mechanics was also referred to as wave mechanics [2]. In the field of nonlinear optics it is known that quantum interference effects can profoundly modify the over-all system response and also lead to new physics [3]. For instance, the electromagnetically induced transparency (EIT) effect [4] can be considered as a destructive interference between the amplitudes of two excitation pathway involving a weak on-resonance probe field and a strong but also on-resonance coupling field. The consequence of such interference effect is the total cancellation of the absorption of the probe field as well as the elimination of the probe propagation phase shift when both one- and two-photon detuning are zero [5].

In the field of nonlinear optics of resonant media quantum interference effect between different excitation pathways have been shown to lead to many novel and intriguing processes [3], including efficient odd- [6–14] and even-photon [15] destructive interference effects, enhanced and suppressed multi-photon ionization processes [11], forward-hyper-Raman suppression [13], suppression of various optical shifts [16] and nonclassical field generation [17–19]. It has been known, however, that such multi-wave mixing interference effects [20–25] usually do not occur if the hyper-Raman terminal state is not allowed to couple radiatively back to the ground state. Indeed, to date there has been no study, theoretical or experimental, on the suppression of forward hyper-Raman gain process by such multi-wave mixing processes.

In this work we show that it is possible to achieve a complete transparency in a hyper-Raman process where the back-coupling to the ground state is not allowed. We show that by carefully choosing operation parameters a nonlinear wave-mixing-induced transparency regime can be established via a dynamic gain cancellation effect. As a result, if a light field with the same frequency as the internally-generated field is injected into the medium it will experience no change in intensity and propagation phase. We emphasize that while this wave-mixing-induced transparency leads to propagation-independent properties similar to that resulted from the well-known odd-photon destructive interference effects [3,4,6–16] it is not an interference effect that leads to electromagnetically induced transparency. This gain-cancellation-based induced transparency may lead to effective suppression of parasitic

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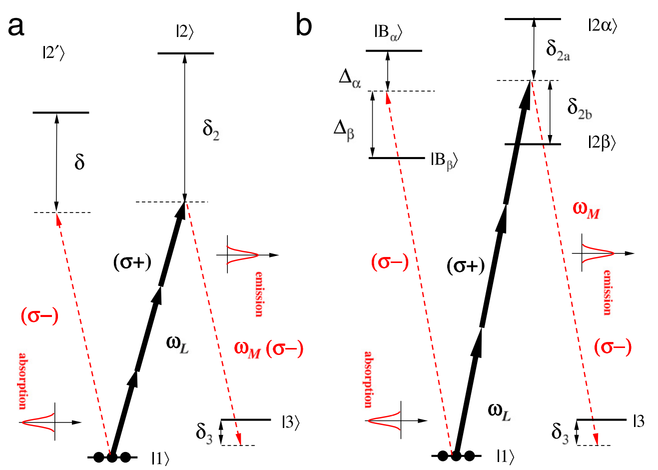

Fig. 1. (Color online) (a) A right-circularly-polarized strong pump field E_L with angular frequency ω_L couples the transition between states $|1\rangle$ and $|2\rangle$ via three-photon process. A left-circularly-polarized weak SFG field E_M with angular frequency ω_M drives $|1\rangle \leftrightarrow |2'\rangle$ and $|2\rangle \leftrightarrow |3\rangle$ transitions simultaneously. (b) Energy levels and laser-field configurations for the experiment.

Raman/hyper-Raman noise field generated in high intensity optical fiber transmissions.

2. Model

We begin by first considering a life-time broadened (such as laser-cooled) three-state atomic medium in a sum-frequency-generation (SFG) configuration (Fig. 1a) where three photons of frequency ω_L from a strong pump field E_L are absorbed simultaneously during the transition $|1\rangle \to |2\rangle$. As the consequence of this three-photon excitation and with appropriate choice of light polarization the dipole-allowed transition $|2\rangle \to |3\rangle$ leads to a SFG field that terminates at the lower excited state $|3\rangle$. Since the SFG field terminal state $|3\rangle$ is not allowed to radiatively couple back to the ground state $|1\rangle$ the SFG field is also referred to as a hyper-Raman field. For this reason we inter-changeably use SFG and hyper-Raman field in this work in describing this generated field. Indeed, this "inelastically-generated" [26] sum-frequency wave-mixing field E_M with frequency ω_M has the feature of a Raman-like process. It propagates co-linearly and grows coherently with the pump field. The main objective of the present work is to show that with appropriate selected states for the hyper-Raman field an additional nearby state can open an effective absorption channel which results in novel features not known before. We show that under suitable operation conditions, a nonlinear third-order effect arising from non-adiabatic correction to the polarization at frequency ω_M can provide an effective gain cancellation mechanism, leading to a mixing-wave-induced transparency where the generated field becomes both concentration and propagation independent.

The energy-level diagram with laser couplings of the system studied is given in Fig. 1a. While the transitions require circularly polarized pump and SFG seed field to enable an additional background absorption channel a mathematical treatment assuming linearly polarized pump and SFG fields is more transparent in demonstrating the underlying physics [27]. Indeed, there is no loss of key physics using this simplified treatment which can also be verified using a density matrix approach. Based on these considerations we write the equations of motion for the state amplitudes under rotating-wave approximation as

$$\dot{A}_1 = i\Omega_{21}^{(3)*} A_2, \tag{1}$$

$$\dot{A}_2 = i d_2 A_2 + i\Omega_{21}^{(3)} A_1 + i\Omega_{23} A_3, \tag{2}$$

$$\dot{A}_3 = i d_3 A_3 + i\Omega_{23}^{*} A_2, \tag{3}$$

where A_j is the amplitude of the state $|j>$, $d_i = \delta_j + i\gamma_i$ with δ_2 and δ_3 being the one- and two-photon detunings, respectively. Here, γ_i is the decay rate of state $|i\rangle$. $\Omega_{21}^{(3)}$ is the effective three-photon Rabi frequency by the pump field and $\Omega_{23} = \Omega_M = D_{23}E_M/\hbar$ is the Rabi frequencies of the hyper-Raman/SFG fields with electric dipole moments of D_{23}. Typically, in a hyper-Raman process $\delta_3 \approx 0$. The additional absorption channel can be introduced if the SFG field is weakly affected by a nearby state $|2'\rangle$ (see Fig. 1a) offered by a background buffer gas. Mathematically, such a perturbative effect by the background gas can be satisfactorily treated by adding a corresponding term in the source term for the Maxwell equation of the hyper-Raman/SFG field. One primary example of such a treatment is the index compensation in sum frequency generation in pure alkali metal vapor with inert background gas for index matching. We note that Eqs. (1)–(3) derived using rotating wave approximations have been successfully used to explain various nonlinear optical multi-photon destructive interference effects, validating the use of such a treatment for the problem presented here.

Solving Eqs. (1)–(3) using the first order non-adiabatic theory in non-depleted ground state approximation we obtained polarization source term for the Maxwell equation for the inelastic SFG field. To the leading order of nonlinear contribution and the first order background absorption, this can be expressed as [28]

$$\begin{aligned}\frac{\partial \Omega_M}{\partial z} + \frac{i}{2k_z}\nabla_\perp^2 \Omega_M &= i\kappa_{32} A_2 A_3^* - i\frac{\kappa_b}{\delta + i\gamma}\Omega_M \\ &= -i\kappa_{32}\left(1 + \frac{|\Omega_M|^2}{d_2 d_3}\right)\frac{|\Omega_{21}^{(3)}|^2}{|d_2|^2}\frac{\Omega_M}{d_3^*} - i\frac{\kappa_b}{\delta + i\gamma}\Omega_M \\ &= (G + i\phi)\,\Omega_M,\end{aligned} \tag{4}$$

where δ and γ are the detuning and the dephasing rate of the state $|2'\rangle$ respectively, and $\kappa_b \approx \kappa_{32} = 2\pi\omega_{23}N|D_{23}|^2/(\hbar c)$ with N being the atom density and the transverse contribution to the wave equation has been neglected. In Eq. (4) we have defined two real quantities

$$\begin{aligned}G &= \kappa_{32}\left[1 - \frac{|\Omega_M|^2\gamma_2}{(\delta_2^2 + \gamma_2^2)\gamma_3}\right]\frac{|\Omega_{21}^{(3)}|^2}{|d_2|^2\gamma_3} - \frac{\kappa_b\gamma}{\delta^2 + \gamma^2} \\ &= (G_0 - \alpha_0) - \alpha_1|\Omega_M|^2,\end{aligned}$$

$$\phi = -\kappa_{32}\left[\frac{|\Omega_M|^2\delta_2}{(\delta_2^2 + \gamma_2^2)\gamma_3}\right]\frac{|\Omega_{21}^{(3)}|^2}{|d_2|^2\gamma_3} - \frac{\kappa_b\delta}{\delta^2 + \gamma^2} = \phi_0 + \phi_1|\Omega_M|^2.$$

with $G_0 = \kappa_{32}|\Omega_{21}^{(3)}|^2/(|d_2|^2\gamma_3)$, $\alpha_0 = \kappa_b\gamma/(\delta^2 + \gamma^2)$, $\alpha_1 = \kappa_{32}\gamma_2|\Omega_{21}^{(3)}|^2/[\gamma_3^2|d_2|^2(\delta_2^2 + \gamma_2^2)]$, $\phi_0 = -\kappa_b\delta/(\delta^2 + \gamma^2)$ and $\phi_1 = -\kappa_{32}\delta_2|\Omega_{21}^{(3)}|^2/[\gamma_3^2|d_2|^2(\delta_2^2 + \gamma_2^2)]$.

The first term in the parenthesis on the right side of Eq. (4) represents the gain characteristics known to hyper-Raman and inelastic-wave-mixing processes [26] whereas the second term is the leading contribution by the third-order correction to the lowest adiabatic approximation of A_2 and A_3. The last term containing κ_b arises from the back ground absorption arises from the near-by state $|2'\rangle$ state (see the left red-dashed arrow in Fig. 1a [29]). Usually, such a background state can be engineered using two species of atomic gases with similar properties. However, an example of single element serves the purpose of illustrating the underlying physics. Consider, for instance, an atomic vapor system with $F = 1, 2$ ground state manifold and assume that the population is initially in the $F = 1, m_F = -1$ state. If we take the three-photon detuning δ_2 (a $\sigma^{(+)}$ pump) to be about 1 GHz on the high energy side of the $F' = 2$ manifold in a D_1-line-like transition and assume that the hyper-Raman field (with $\sigma^{(-)}$ polarization) terminates on the $F = 2, m_F = +1$ state that is 1.3 GHz above the $F = 1$ manifold, then the hyper-Raman field can also couple the ground state $F = 1, m_F = -1$ to $F' = 2, m_{F'} = -2$ state with a smaller red detuning $\delta = -300$ MHz. The idea is to use this background state to introduce an additional absorption that can slightly under-compensate the efficient hyper-Raman gain, i.e., $G_0 - \alpha_0 \sim 0^+$, making the nonlinear third-order correction term an effective trigger for total propagation gain cancellation even with a weak generated field. This may lead to efficient suppression of parasitic Raman/hyper-Raman generation in fiber optical data links.