

Electromagnetically induced transparency-like effect in the degenerate triple-resonant optical parametric amplifier

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We investigate experimentally the absorptive and dispersive properties of the triple-resonant optical parametric amplifier (OPA) for the degenerate subharmonic field. In the experiment the subharmonic field is utilized as the probe field and the harmonic wave as the pump field. We demonstrate that the electromagnetically induced transparency (EIT)-like effect can be simulated in the triple-resonant OPA when the cavity linewidth for the harmonic wave is narrower than that for the subharmonic field. However, this phenomenon cannot be observed in a double-resonant OPA. The narrow transparency window appears in the reflected field. Especially in the measured dispersive spectra of the triple-resonant OPA, a very steep variation of the dispersive profile of the subharmonic field is observed, which can result in a slow light as that observed in an atomic EIT medium. © 2008 Optical Society of America
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Quantum coherence in atoms has led to a variety of novel phenomena. In electromagnetically induced transparency (EIT), destructive quantum interference introduced by a strong coupling laser cancels the absorption from the ground state to coherent superposing upper states [1,2]. The observation of non-absorbing resonance through atomic coherence has led to novel concepts, such as lasing without inversion [3]. Since the EIT linewidth can be made extremely narrow, the resulting steep linear dispersion has been used to reduce the velocity of light. This technique has been developed for coherent optical information storage and to freeze light [4–8].

Since EIT results from destructive quantum interference, it has been recognized that similar coherence and interference effects can also occur in classical systems, such as plasma [9–11], coupled optical resonators [12–18], and mechanical or electric oscillators [19,20]. Particularly, the phenomenology of the EIT and the dynamic Stark effect are studied theoretically in a dissipative system composed by two coupled oscillators using the quantum optics model in [21]. The optical parametric amplifier (OPA) is one of the most important nonlinear and quantum optical devices. Recently, we studied the coherence phenomena in the phase-sensitive degenerate OPA inside a cavity [22,23]. This phenomenon results from the interference between the harmonic pump field and the subharmonic seed field in the OPA. The destructive and constructive interferences correspond to optical parametric deamplification and amplification, respectively. The absorptive response of an optical cavity for the probe field is changed by optical parametric interaction in the cavity. Agarwal [24] generalized our observation of interferences in the classical domain [22] to in the quantum domain and studied the interferences in the quantum fluctuations of the output fields from a parametric amplifier when the cav-

ity is driven by a quantized field at the signal frequency.

In the previous works [22,23] we studied the absorptive and dispersive properties of the degenerate double-resonant OPA where only the degenerate subharmonic field resonated inside the cavity but the pump field did not. Although in the experiment with the double-resonant OPA the mode splitting in the transmission spectra [22] and the M shape in the reflection spectra were observed experimentally [23], the shape of the phase shift of the reflected field was unchanged [23]. Further, we investigated the triple-resonant OPA theoretically, in which both the subharmonic and harmonic wave simultaneously resonate inside the cavity [23]. We found that the EIT-like effect can be simulated with a triple-resonant OPA. In this Letter, we present the results of the experimental investigation on the absorptive and dispersive properties of a triple-resonant OPA for the subharmonic field. The frequency and polarization of signal and idler fields in the OPA are totally degenerate. We demonstrate that the EIT-like effect can be simulated in the OPA when the cavity linewidth for the harmonic wave is narrower than that for the subharmonic field. A narrow transparency window appears in the reflected field. Especially, we measured the dispersive spectra of the triple-resonant OPA, and a very steep variation in the dispersive profile was observed.

The experimental setup is shown schematically in Fig. 1, which is similar to that used in our previous work [23]. A diode-pumped intracavity frequency-doubled cw ring Nd:YVO₄/KTP single-frequency laser serves as the light sources of the pump wave (the second-harmonic wave at 532 nm) and the probe wave (the subharmonic wave at 1064 nm) for the OPA. We actively control the relative phase between the subharmonic and the pump field by adjusting the

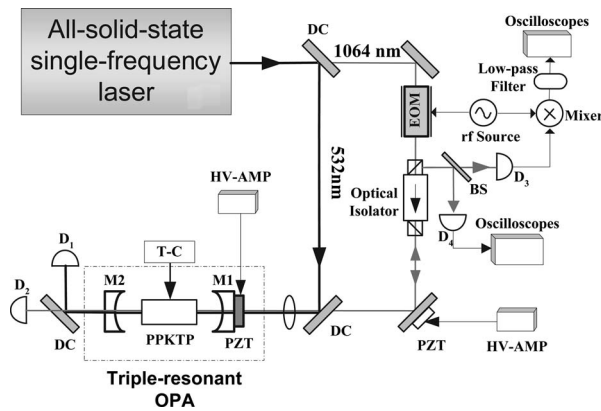


Fig. 1. Schematic of the experimental setup. DC, dichroic mirror; $\lambda/2$, half-wave plate; D_1, D_2, D_3, D_4 , detectors; T-C, temperature controller; HV-AMP, high voltage amplifier; PZT, piezoelectric transducer; EOM, electric-optic modulator.

phase of the subharmonic beam with a mirror mounted upon a piezoelectric transducer (PZT). Both beams are combined together by a dichroic mirror and injected into the OPA cavity. The OPA consists of a type I periodically poled KTiOPO_4 (PPKTP) crystal (12 mm long) and two external mirrors separated by 61 mm. Two end faces of the crystal are polished and coated with an antireflection coating for both wavelengths of 532 and 1064 nm. The crystal is mounted in a copper block, whose temperature is actively controlled at the millidegrees Kelvin level around the phase-match temperature for the optical parametric process (31.3°C). The input coupler $M1$ is a 30 mm radius-of-curvature mirror with a power reflectivity of 99% for 1064 nm in the concave and 97% for 532 nm, which is mounted upon a PZT for adjusting the length of the optical cavity. The back mirror $M2$ is a 30 mm radius-of-curvature mirror with a reflectivity of 93% for 1064 nm and a high reflectivity coefficient for 532 nm in the concave. This structure forms the triple-resonant OPA, in which the pump wave and the frequency-degenerated idler and signal waves are all resonating inside the same cavity. This is distinctly different from our previous setup. The cavity is an undercoupled resonator for the subharmonic field owing to $\gamma_{in} < \gamma_c + \gamma_l$, where γ_l , γ_c , and γ_{in} are the decay rates of the subharmonic field resulting from internal losses, input mirror, and back mirror, respectively. The cavity linewidth for the harmonic wave is narrower than for the subharmonic field because the total damping of the pump field is much less than that of the subharmonic field ($\gamma_b \ll \gamma$). Owing to the high nonlinear coefficient of PPKTP, the measured threshold power is $P_{th} = 90$ mW. To measure the phase of the reflected beam we employ the Pound–Drever–Hall method (or frequency-modulation spectrum) [25–30], which provides a way to indirectly measure the phase. The frequency of the injected subharmonic field is modulated with an electric-optic modulator (EOM), driven by a local oscillator with a radio frequency of 100 MHz. Here the depth of frequency modulation is very small; thus we can observe only two sidebands. The reflected beam

is picked off with an optical isolator and sent into a photodetector D_3 , whose output is compared with the local oscillator's signal via a mixer. A low-pass filter on the output of the mixer extracts the low-frequency signal, which is called the error signal. When the frequency of the injected subharmonic field is near resonance and the modulation frequency is high enough, the sidebands are out of the resonance and the error signal is the imaginary part of the reflected field. In our scheme the cavity is an undercoupled resonator whose dispersive response results in fast light [18]. When an undercoupled resonator is far from critically coupled the imaginary part of the reflected field approximates to the phase shift.

First, we measured the spectra of the subharmonic reflection, transmission, and phase shift of the reflection as the functions of the cavity detuning at the case without the existence of the pump field, which are shown in Fig. 2. Two small sideband modes generated by frequency modulation can be seen in the transmission spectrum (see arrows in Fig. 2b). Then we hold the frequencies of the injected subharmonic and the pump field at $\omega_p = 2\omega$, and the phase difference $\varphi = \pi/2$ (i.e., the OPA at the state of deamplification), and two optical fields resonate simultaneously in the OPA by adjusting the cavity length and the temperature of PPKTP. The cavity length is scanned around the resonant point. In Fig. 3 curves e, f , and g show the spectra of the subharmonic reflection, transmission, and phase shift of the reflection, respectively, with the pump power below the threshold $P = 0.15P_{th}$, and curves h, j , and k with $P = 0.3P_{th}$. We can see that the narrow transparency window appears in the reflection spectrum and is accompanied by a very steep variation of the dispersive profile whose dispersive response can result in slow light as that in the EIT medium. This experimental result is in good agreement with the theoretical predictions in [23].

The observed phenomenon is easily understood: Since the narrow absorption and dispersion of the pump field are introduced into the subharmonic field via the parametric interaction in the triple-resonant OPA, the reflected field of the subharmonic field presents the EIT-like effect [23]. For the case of EIT in atomic systems the analogous condition of $\gamma_b \ll \gamma$ is obtained when a pair of lower energy states have a long lifetime. Note that we did not observe the phenomena under higher pump power as that predicted theoretically in [23]. There are two main reasons. One is that the OPA will produce a large quantum fluctuation on the subharmonic field under higher pump power. The other is that the pump field had the

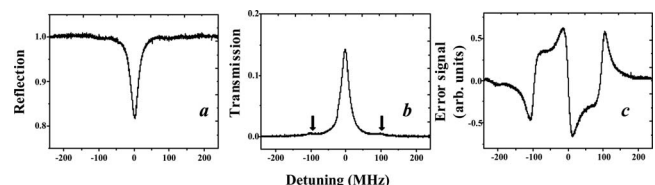


Fig. 2. Spectra of the subharmonic reflection, transmission, and phase shift of the reflected field as a function of the cavity detuning when the pump field is blocked.

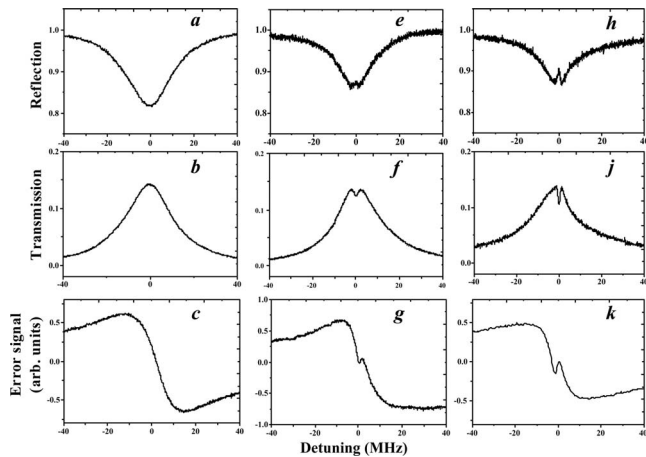


Fig. 3. Spectra of the subharmonic reflection, transmission, and phase shift of the reflected field as a function of the cavity detuning for different pump powers. *a–c* correspond to Fig. 2 with narrow frequency detuning. *e–g* at the pump power $0.15P_{th}$, *h, j*, and *k* at $0.3P_{th}$.

strong thermal effect at the high pump power, which would influence the constructed triple resonance. When scanning the cavity length the thermoinduced effect for the pump field was observed as shown in Fig. 4, from which we can see it seems like the Kerr nonlinear effect. The transmission profile of the pump field appears as a large asymmetry at a higher pump power when the cavity length is scanned from the shorter to the longer and vice versa. Thus it is difficult to measure the unusual line shape in the reflection spectrum and the steep variation of the dispersive profile for the triple-resonant OPA in the case of the strong parametric coupling between two fields.

In conclusion, we have investigated experimentally the absorptive and dispersive response of the reflected subharmonic field from a triple-resonant phase-sensitive OPA. It is demonstrated that an EIT-like effect is simulated when the cavity linewidth for the harmonic wave is narrower than for the subharmonic field. The narrow transparency window appears in the reflected field and is accompanied by a very steep variation of the dispersive profile. This novel system accompanying parametric gain for the probe signal will be important for practical optical and photonic applications such as in optical filters and delay lines, and is closely related to the coherent phenomenon of EIT as that predicted for quantum systems.

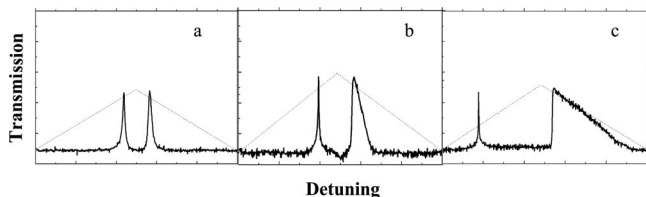


Fig. 4. Spectra of transmission of the pump field as a function of the cavity detuning for different pump powers: *a*, at $0.2P_{th}$; *b*, at $0.5P_{th}$; *c*, at $0.9P_{th}$. The dotted curve represents the voltage on PZT, which denotes the cavity length scanned from shorter to longer, then from longer to shorter.

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