Influence of Cavity Lifetime on High-Finesse Microcavity Two-Photon Absorption Photodetectors

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***Abstract*—For optical pulse incidence as compared with continuous-wave incidence, the enhancement of two-photon absorption inside a high-finesse planar microcavity is reduced, the pulse inside the cavity and the cavity spectrum are broadened. The analysis shows that for transform-limited pulse incidence, the true pulsewidth and the cavity frequency resolution can be estimated if the cavity lifetime or the cavity bandwidth has been obtained from the reflection or transmission spectrum of the cavity.**

***Index Terms*—Autocorrelation, finesse, microcavity, photodetector, two-photon absorption (TPA).**

I. INTRODUCTION

TWO-PHOTON absorption (TPA) in semiconductors can be employed to correlate very short optical pulses [1]. Autocorrelation of optical pulses as short as 6 fs by TPA in a GaAsP photodiode has been reported [2]. Applications of TPA in optical telecommunications have also been reported, such as all-optical demultiplexing [3], optical clock recovery [4], and optical performance monitoring [5]. Unfortunately, TPA in semiconductors is always a very weak process. To improve the detection sensitivity, waveguide detectors with very long absorption length [6] and avalanche photodiodes with very high internal gain have been used.

Recently, enhancement of two-photon excited fluorescence in the defect layer of a one-dimensional photonic crystal has been reported [8]. Strong improvement of TPA efficiency in a high-finesse GaAs planar microcavity has also been reported [9]. These microcavities consist of two highly reflective Bragg mirrors sandwiching a bulk active layer. In the active layer, the electric field can be strongly enhanced which consequently results in high TPA. For continuous-wave (CW) incidence, it is expected that higher reflectivities from the Bragg mirrors will make the electric field in the active layer stronger so the enhancement of TPA will be higher. For optical pulse incidence, the situation becomes a little more complex. As we know, the incident field needs several round-trips to build up the intensity inside a Fabry–Pérot (FP) cavity. As the cavity reflectivity or the cavity finesse gets higher, the intensity build-up time will get longer and the intensity will finally saturate at a higher level. For short optical pulses their duration may be comparable to or even less than this build-up time, so it is expected that they will not be enhanced as much as their CW counterpart. In this letter, we analyze the build-up time (in the following it is substituted by a more strict concept "cavity lifetime") influence of the TPA enhancement in the microcavity TPA photodetector (MTPAPD) for optical pulse incidence. The planar microcavity is also an FP cavity which has a frequency resolution capability. In this letter, we also analyze how the cavity resolution is influenced as the incident signal is changed from CW to a short optical pulse.

II. THEORY

The electric field of the incident pulse can be expressed as

$$E_{\rm in}(t) = e_{\rm in}(t)\exp(i\omega_m t)/2 + c.c. \equiv E_{\rm in}^{+}(t) + E_{\rm in}^{-}(t) \quad (1)$$

where ω_m is the cavity mode frequency

$$e_{\rm in}(t) = p(t)\exp\left[i(\omega_0 - \omega_m)t\right] \equiv p(t)\exp(i\Delta\omega t) \quad (2)$$

is assumed to be a slowly varying function, where $p(t)$ is the pulse envelope and ω_0 is the pulse carrier frequency which deviates from the cavity mode frequency by $\Delta\omega$. We focus on pulsewidths around 1 ps or longer because, as the following analysis shows, the cavity enhancement mechanism works well for such pulsewidths and does not work very efficiently if the pulsewidths get much less than 1 ps. The electric field has been normalized with its square representing the power flux. The Fourier transform of the positive frequency part in (1) is $\widetilde{E}_{\rm in}(\Omega) = \widetilde{e}_{\rm in}(\Omega - \omega_m)/2 \equiv \widetilde{e}_{\rm in}(\delta\omega)/2$. In the frequency domain, the electric field inside the cavity is correlated with the incident wave through the transfer function as $\widetilde{E}_c^{+}(\Omega, z) = \widetilde{E}_{\rm in}^{+}(\Omega)\Gamma(\Omega, z)$. For a normally incident wave, the transfer function can be expressed as in (3), shown at the bottom of the next page, where d is the cavity thickness, $\beta = n\Omega/c$ is the wave number inside the cavity, T_0 is the power transmission of the top mirror (incident from air), R_1 and R_2 are power reflectivities of the top and bottom mirrors (incident from inner of the cavity), and ϕ_ν are phase shifts associated with the transmission and reflection coefficients (ν representing subscripts t_0, r_1 and r_2). The equation $2\beta d + \phi_{r_1} + \phi_{r_2} = 2m\pi$ determines the cavity mode frequency ω_m. For lossless top mirrors, we have $T_0 = 1 - R_1$. In a small frequency range around the cavity mode frequency, we can approximate the phase shifts ϕ_ν as $\phi_\nu \approx \tau_\nu(\Omega - \omega_m) \equiv \tau_\nu\delta\omega$, where τ_ν is the group delay of corresponding mirrors, and the phase shift at exactly the cavity mode frequency ω_m is assumed to be zero. The wave

Manuscript received November 27, 2006; revised January 9, 2007. This work was supported by SFI under its CSET Centre for Telecommunication Value Driven Research (CTVR), Grant 03/CE3/I405.

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Digital Object Identifier 10.1109/LPT.2007.892884

number β can be approximated as $\beta \approx \beta_m + \delta\omega v_g^{-1}$, where β_m is the wave number at ω_m, v_g is the group velocity inside the cavity. In (3), the numerator of the transfer function describes the standing wave distribution and the denominator describes the enhancement achieved by the reflection from the mirrors. Now we make a simplifying approximation by assuming that the variation of the transfer function with wavelength is mainly determined by the denominator variance; i.e., we neglect the variance of the standing wave distribution with wavelength. This would be a good approximation for high-finesse microcavities because the wavelength change would be just a few nanometres. The transfer function can now be changed to

$$\Gamma(\Omega, z) \approx \frac{\exp\left(-i\delta\omega\tau_{t_0}\right) f(z)}{1 + \frac{R}{2(1-R)}\tau^2\delta\omega^2 + i\frac{R}{1-R}\tau\delta\omega} \tag{4}$$

where

$$f(z) = \frac{\sqrt{T_0}\left(\exp(-i\beta_m z) + \sqrt{R_2}\exp(i\beta_m z)\right)}{1-R} \tag{5}$$

is the field distribution inside the cavity for the cavity mode frequency, $\tau = 2dv_g^{-1} + \tau_{r_1} + \tau_{r_2}$ is the round-trip group delay, $R = (R_1 R_2)^{1/2}$. If $R > 0.9$, the error of the above approximation is less than 10% and the error decreases as R or the cavity finesse $\pi R^{1/2}/(1-R)$ increases. $|\Gamma(\Omega, z)|^2$ calculated from (4) has a Lorentzian lineshape which has a full-width at half-maximum (FWHM) given by $\gamma_{c,\omega} = 2(1-R)/(\tau R^{1/2})$, where the subscript ω indicates that $\gamma_{c,\omega}$ is expressed in angular frequency. If expressed in wavelength, we have $\gamma_{c,\lambda} = \lambda_m^2 \gamma_{c,\omega}/(2\pi c)$. $\gamma_{c,\omega}$ and $\gamma_{c,\lambda}$ are called cavity bandwidth in the following. The cavity bandwidth can be calculated from the reflection or transmission spectrum of the cavity. The cavity lifetime is defined as $T_c = 1/\gamma_{c,\omega} = \lambda_m^2/(2\pi c\gamma_{c,\lambda})$. Using the approximated transfer function (4) and assuming the field inside the cavity has the same form as (1), we can obtain the following equation:

$$\widetilde{e}_c(\delta\omega, z) = \frac{\widetilde{e}_{\mathrm{in}}(\delta\omega)\exp\left(-i\delta\omega\tau_{t_0}\right)}{1 + 2(1-R)T_c^2\delta\omega^2 + i2\sqrt{R}T_c\delta\omega} f(z) \tag{6}$$

where the definition of cavity lifetime has been used. After transforming into the time domain, we obtain

$$\left[2(R-1)T_c^2\frac{\partial^2}{\partial t^2} + 2\sqrt{R}T_c\frac{\partial}{\partial t} + 1\right] e_c(t) = e_{\mathrm{in}}\left(t - \tau_{t_0}\right). \tag{7}$$

The field dependence on position inside the cavity is given by (5). Its dependence on time can be solved from (7). Therefore, the electric field inside the cavity can now be expressed as $E_c(t,z) = e_c(t)f(z)\exp(i\omega_m t)/2 + c.c.$ We can calculate the intensity averaged in an optical cycle as $I_c(t,z) = |e_c(t)|^2 |f(z)|^2/2$. If the incident pulse intensity is far from the saturation range, we can neglect the TPA influence on the field variation with time and position because TPA in semiconductors is always a weak process. Assuming TPA is an instantaneous process, we can calculate the TPA inside the cavity based on the pulse intensity. Here we define a relative value, the TPA enhancement factor, to characterize the cavity enhancement effect. It is defined in the following equation as the ratio between the TPA in the active layer calculated with and without the cavity effect:

$$\zeta = \frac{\int_{-\infty}^{+\infty} dt\, |e_c(t)|^4}{\int_{-\infty}^{+\infty} dt\, |e_{\mathrm{in}}(t)|^4} \cdot \frac{\int_0^d dz\, |f(z)|^4}{d} \equiv \zeta_t \cdot \zeta_z \tag{8}$$

where ζ_z can be calculated from (5) as $\zeta_z = T_0^2(1 + R_2^2 + 4R_2)(1-R)^{-4}$, which as the formula shows will increase monotonically as the reflectivity increases. For CW incidence we have $e_{\mathrm{in}}(t) = \exp(i\Delta\omega t)$ from (2), where $\Delta\omega$ is the frequency deviation between the incident wave and the cavity mode. From (6) and (8), we can obtain $\zeta_t = (1 + 4\Delta\omega^2\gamma_{c,\omega}^2)^{-2}$, which has an FWHM of $(2^{1/2}-1)^{1/2}\gamma_{c,\omega} \approx 0.643\gamma_{c,\omega}$ that is smaller than $\gamma_{c,\omega}$ because TPA is dependent on the electric field to the power of four. This value represents the frequency resolution of the cavity under CW incidence. Furthermore if $\Delta\omega = 0$, we have $\zeta_t = 1$ and $\zeta = \zeta_z$, which means that ζ_z is the TPA enhancement factor for the CW incidence with the incident wavelength aligned with the cavity mode. The following analysis also shows that ζ_z is the maximum TPA enhancement factor. ζ_t causes the total TPA enhancement to be less than ζ_z if the incident pulse duration is comparative to or less than the cavity lifetime. The TPA enhancement is also less than ζ_z if the pulse carrier frequency ω_0 is detuned from the cavity resonance frequency ω_m. We call ζ_t the correction factor of the TPA enhancement in the following.

III. Numerical Analysis

We take the incident pulse as a transform-limited hyperbolic secant pulse; i.e., $p(t)$ in (2) is $\mathrm{sech}(1.763t/T_p)$, where T_p is the pulsewidth (intensity FWHM). The pulse intensity spectrum has an FWHM of $\gamma_{p,\omega} \approx 2.0/T_p$. In the following, all time quantities are normalized by the cavity lifetime T_c. First we find the pulse inside the cavity is always asymmetrically broadened with a slowly decaying tail imposed by the cavity and little difference is produced if the cavity lifetime is kept constant but the reflectivity and cavity length vary. In the following analysis, we set the reflectivity to be 0.95. For this reflectivity, the cavity finesse is 61 and the TPA enhancement factor for CW incidence, ζ_z as defined in (8), is 9100 assuming the bottom mirror reflectivity is very close to 1.0.

One important application of TPA in semiconductors is to determine the pulsewidth of very short optical pulses through correlation measurements. The microcavity can greatly enhance TPA; however, it also broadens the pulse inside the cavity which could result in an overestimation of the pulsewidth. Fig. 1 shows the broadening factor of the autocorrelation trace (ACT) versus the incident pulsewidth normalized by the cavity lifetime. The broadening factor is defined as the ratio between the FWHM of the ACT calculated from the pulse inside the cavity and from the incident pulse directly. The variation of the correction factor of the TPA enhancement with the normalized incident pulsewidth is also presented. It is seen that if the pulsewidth is equal to

$$\Gamma(\Omega, z) = \frac{\sqrt{T_0}\exp\left(-i\phi_{t_0}\right)\left(\exp(-i\beta z) + \sqrt{R_2}\exp\left(-i\left(2\beta d + \phi_{r_2}\right)\right)\exp(i\beta z)\right)}{1 - \sqrt{R_1 R_2}\exp\left(-i\left(2\beta d + \phi_{r_1} + \phi_{r_2}\right)\right)} \tag{3}$$

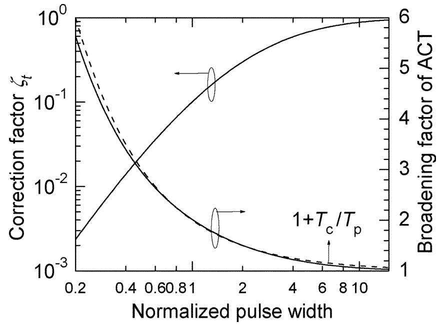

Fig. 1. Broadening factor of the ACT and correction factor of the TPA enhancement ζ_t versus the incident pulsewidth normalized by the cavity lifetime.

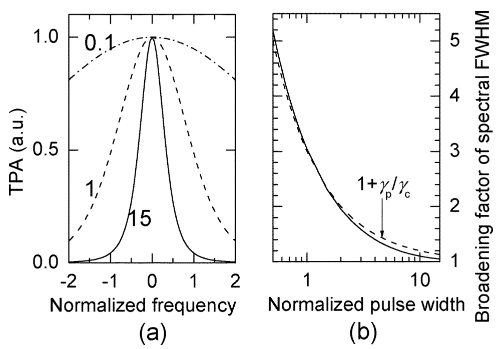

Fig. 2. (a) TPA versus deviation between the pulse carrier frequency and the cavity mode frequency normalized by the cavity bandwidth. The normalized pulsewidth is equal to 15, 1, and 0.1, respectively. (b) Broadening factor of the cavity spectral FWHM versus normalized pulsewidth.

the cavity lifetime, i.e., the normalized pulsewidth equals one, the FWHM of the ACT is almost doubled. The broadening effect is even stronger as the pulsewidth becomes less than the cavity lifetime. So in these situations, the pulsewidth cannot be extracted from the ACT directly without taking the cavity lifetime influence into account. It is also found that a simple formula $1 + T_c/T_p$ gives a good approximation to the broadening factor of the ACT as seen from Fig. 1. This result shows one simple way to extract the intrinsic pulsewidth. The cavity lifetime can be calculated from the cavity bandwidth (FWHM of the reflection or transmission spectrum of the cavity) as introduced above. After obtaining the overestimated pulsewidth from the broadened ACT, the intrinsic pulsewidth can be calculated by subtracting the cavity lifetime. The correction factor of the TPA enhancement ζ_t is just 0.1 if the pulsewidth equals the cavity lifetime and decreases very quickly as the pulsewidth becomes less than the cavity lifetime.

The microcavity structure also gives the MTPAPD frequency resolution capability which makes it possible to select channels in the wavelength-division-multiplexing communication system without an external filter placed before it. In the following, we consider the influence of the cavity lifetime on the frequency resolution of the MTPAPD. The resolution can be represented by the cavity spectral FWHM with TPA as the response. For pulse incidence, we examine the cavity spectral FWHM by keeping the pulse unchanged and scanning the pulse carrier frequency. Fig. 2(a) presents the spectrum for the normalized pulsewidth equal to 15, 1, and 0.1, respectively. It is seen that the spectrum becomes broader as the pulsewidth decreases. Fig. 2(b) presents the broadening factor of the spectral FWHM versus the normalized incident pulsewidth. The broadening is relative to the CW incidence situation. As expected for an incident pulse much longer than the cavity lifetime, the spectral FWHM is close to the value for CW incidence. If the normalized pulsewidth is 2.0 (the pulse spectral width equals to the cavity bandwidth in this situation), the spectral FWHM is almost twice the value for CW incidence. It is also seen that a simple formula $1 + \gamma_p/\gamma_c$ gives a good approximation to the broadening factor. This approximation can help us to quickly find the spectral FWHM of the MTPAPD for pulse incidence because both the pulse intensity spectrum and the cavity bandwidth can be measured.

IV. Conclusion

We have analyzed the cavity lifetime influence on the MTPAPD response. For pulse incidence, the pulse inside the cavity will be broadened by the cavity lifetime and the TPA enhancement is also reduced compared with the CW incidence. The cavity frequency resolution is also weakened. The broadening of the ACT and the cavity spectrum for pulse incidence can be easily estimated if the cavity lifetime or the cavity bandwidth is obtained from the reflection or transmission spectrum of the cavity.

Acknowledgment

The authors would like to thank D. Kilper and M. Dinu of Bell Laboratories, Crawford Hill, for valuable discussions.

References

[1] Y. Takagi, T. Kobayashi, K. Yoshihara, and S. Imamura, "Multiple- and single-shot autocorrelator based on two-photon conductivity in semiconductors," *Opt. Lett.*, vol. 17, no. 9, pp. 658–660, 1992.

[2] J. K. Ranka, A. L. Gaeta, A. Baltuska, M. S. Pshenichnikov, and D. A. Wiersma, "Autocorrelation measurement of 6-fs pulses based on the two-photon-induced photocurrent in a GaAsP photodiode," *Opt. Lett.*, vol. 22, no. 17, pp. 1344–1346, 1997.

[3] B. C. Thomsen, L. P. Barry, J. M. Dudley, and J. D. Harvey, "Ultrahigh speed all-optical demultiplexing based on two-photon absorption in a laser diode," *Electron. Lett.*, vol. 34, no. 19, pp. 1871–1872, 1998.

[4] R. Salem and T. E. Murphy, "Broad-band optical clock recovery system using two-photon absorption," *IEEE Photon. Technol. Lett.*, vol. 16, no. 9, pp. 2141–2143, Sep. 2004.

[5] S. Wielandy, M. Fishteyn, and B. Zhu, "Optical performance monitoring using nonlinear detection," *J. Lightw. Technol.*, vol. 22, no. 3, pp. 784–793, Mar. 2004.

[6] F. R. Laughton, J. H. Marsh, and A. H. Kean, "Very sensitive two photon absorption GaAs/AlGaAs waveguide detector for an autocorrelator," *Electron. Lett.*, vol. 28, no. 17, pp. 1663–1665, 1992.

[7] C. Xu, J. M. Roth, W. H. Knox, and K. Bergman, "Ultra-sensitive autocorrelation of 1.5 μm light with single photon counting silicon avalanche photodiode," *Electron. Lett.*, vol. 38, no. 1, pp. 86–88, 2002.

[8] J. Y. Ye, M. Ishikawa, Y. Yamane, N. Tsurumachi, and H. Nakatsuka, "Enhancement of two-photon excited fluorescence using one-dimensional photonic crystals," *Appl. Phys. Lett.*, vol. 75, no. 23, pp. 3605–3607, 1999.

[9] H. Folliot, M. Lynch, L. P. Barry, A. L. Bradley, L. A. Dunbar, J. Hegarty, J. F. Donegan, J. S. Roberts, and G. Hill, "Two-photon absorption photocurrent enhancement in bulk AlGaAs semiconductor microcavities," *Appl. Phys. Lett.*, vol. 80, no. 8, pp. 1328–1330, 2002.