Resonance Tuning of Two-Photon Absorption Microcavities for Wavelength-Selective Pulse Monitoring

T. Krug, W. H. Guo, J. O'Dowd, M. Lynch, A. L. Bradley, J. F. Donegan, P. J. Maguire, L. P. Barry, and H. Folliot

***Abstract*—We show the potential use of a single photodetector for multichannel pulse monitoring. Two-photon absorption in a microcavity structure is used as the nonlinear optical technique for pulse monitoring. Angle tuning of the device allows the resonance to be tuned. For the device studied here that is optimized for 2-ps pulses, a possible tuning range of 55 nm is shown.**

***Index Terms*—Cavity resonator filters, cavity resonators, demultiplexing, detectors, photodetectors, tuning, wavelength-division multiplexing (WDM).**

I. Introduction

MULTIWAVELENGTH detectors for ultrafast pulse monitoring in dense wavelength-division-multiplexing (DWDM) systems are in high demand due to rapid progress of high-capacity optical networks. The precise measurement of a signal pulse with high spectral and temporal resolution is an important requirement for realizing >100-Gb/s optical transmission in the near future. Two-photon absorption (TPA) in semiconductors as an optical nonlinear effect is an attractive candidate for optical autocorrelation of short pulses and all-optical switching and sampling of high-speed optical data signals in optical time-division-multiplexed systems [1], [2]. In this letter, we demonstrate a simple approach for accurately detecting different wavelengths in a DWDM system using a single detector. The addressed detector is a TPA microcavity, optimized for 2-ps pulses as this is the pulsewidth available from our pulse source. The TPA detector can be optimized for the pulsewidth of any particular system by adjusting the cavity finesse [3]. Such a detector will find use in 160-Gb/s communications systems which operate with 2-ps pulses. The enhancement of the TPA-induced photocurrent (by a factor of 10 000) due to the cavity finesse greatly improves the sensitivity and enables the implementation of the TPA microcavity as a practical monitoring element in high-speed optical systems characterized by low peak power pulses [4]. The cavity nature of the device allows the resonance frequency to be tuned as a function of angle [5]. Therefore, each channel, corresponding to a different wavelength, in a 160-Gb/s DWDM system can be selected by angle tuning the TPA microcavity. The resonance wavelength is a maximum at normal incidence and the resonance of the optical sampling system can be tuned to lower wavelengths over a wide wavelength range.

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II. Experimental Setup

The TPA microcavity structure, performance, response, and use as an single wavelength autocorrelator has been described in detail previously [6]. This letter addresses specifically the angle dependent TPA response and potential use in DWDM systems. Our experimental setup allowed us to tune the incident angle of the light on the device from minus to plus 45° with respect to normal incidence. The angle tuning was done in the $z-x$ plane and rotational symmetry around the growth axis of the device was assumed. The light was focused onto the device using a 0.20-NA lens. Using such a lens, the angle contribution due to the focusing effect is smaller than the acceptance angle of the microcavity device. The diameter of the focused beam waist was about 5 μm. The generated TPA photocurrent was measured using a standard lock-in amplifier technique.

III. Modelling and Experimental Results

Using the transfer matrix model (TMM), we have analyzed the reflection and transmission spectrum of our microcavity structure. The total phase shift ψ inside the cavity for one round-trip is the important quantity, which determines the resonance behavior of the TPA cavity. We outline a novel approach below in which analytic expressions are an approximation to the TMM for the cavity layout and are presented in order to clearly compare the experimental results with theoretical predictions, as well as to extrapolate the signal TPA response beyond the experimentally available range. It is also worth noting that this analytic treatment has been compared with the results of the TMM approach and good correspondence between the two approaches has been found for simple cavity structures. For the modeling results in Figs. 1–3, the numerical results for the two models are within 1%. For a plane wave incident at angle θ onto the planar microcavity, the TPA inside the cavity can approximately be expressed as

$$A_{\mathrm{TPA}} \approx \beta I_{\mathrm{in}}^2 \varsigma F^2 \cos^2(\theta) \qquad (1)$$

where β is the TPA coefficient, I_{in} is the intensity of the incident plane wave, ζ is the TPA enhancement factor for the plane wave of normal incidence with the wavelength equal to λ_0, the resonant cavity wavelength at normal incidence, and

$$F = [1 + 2R(1-R)^{-2}[1-\cos(\psi)]]^{-1} \quad (2)$$

where $R = (R_t R_b)^{1/2}$, $R_{t,b}$ is the reflectivity of the top/bottom quarter-wavelength Bragg mirror, and

$$\psi(\lambda,\theta) = 4\pi\lambda^{-1}d\sqrt{n_a^2 - \sin^2(\theta)} + \phi_t(\lambda,\theta) + \phi_b(\lambda,\theta) \quad (3)$$

where d and n_a are the active layer thickness and the active layer refractive index, respectively, λ is the incident wavelength on the device; $\phi_{t,b}$ is the phase shift of the front/back distributed Bragg reflection (DBR). The equation $\psi(\lambda, 0) = 2m\pi$ determines the cavity mode wavelength at normal incidence, λ_0. As the active refractive index used is $n_a \approx 3$, for angles $\theta < 70°$ the term $\sin(\theta)/n_a^2$ is smaller than 0.1 and we use the following approximation: $(n_a^2 - \sin^2(\theta))^{1/2} \approx n_a - \sin^2(\theta)/2n_a$. The same approximation has been used to calculate the phase shift of the front/back DBR. As the incident wavelength deviates from λ_0 or the incident angle deviates from the normal incidence, we have the phase shift ψ deviating from $2m\pi$ by

$$\Delta\psi \approx -\frac{4\pi n_a d}{\lambda_0^2}\Delta\lambda - \frac{2\pi d}{\lambda_0 n_a}\sin^2(\theta) + \Delta\phi_t + \Delta\phi_b \quad (4)$$

where the refractive index dispersion is neglected and

$$\Delta\phi_{t,b} \approx -\frac{4\pi D_{t,b}^{\lambda}}{\lambda_0^2}\Delta\lambda - \frac{2\pi D_{t,b}^{\theta}}{\lambda_0}\sin^2(\theta) \quad (5)$$

where $D_{t,b}^{\lambda,\theta}$ is in units of length and is determined by the DBR structure. In the approximation of the limiting case where the number of the DBR mirror pairs goes to infinity, we have

$$D_t^{\lambda} = D_b^{\lambda} = \frac{n_l \lambda_0}{4(n_h - n_l)} \quad (6a)$$

$$D_t^{\theta} = D_b^{\theta} = \frac{\lambda_0}{4(n_h^2 - n_l^2)}\left(\frac{n_h}{n_l} + \frac{n_l^2}{n_h^2}\right) \quad (6b)$$

where the refractive index dispersion is also neglected, $n_{h,l}$ is the high/low refractive index of the composition material of the DBRs. This approximation is used because we consider a cavity with high finesse and a large number of DBR mirror pairs. Combining (4) and (5) we obtain

$$\begin{aligned}\Delta\psi &\approx -\frac{4\pi(n_a d + D_t^{\lambda} + D_b^{\lambda})}{\lambda_0^2}\Delta\lambda \\ &\quad - \frac{2\pi\left(d n_a^{-1} + D_t^{\theta} + D_b^{\theta}\right)}{\lambda_0}\sin^2(\theta) \\ &\equiv -\frac{4\pi D^{\lambda}}{\lambda_0^2}\Delta\lambda - \frac{2\pi D^{\theta}}{\lambda_0}\sin^2(\theta). \quad (7)\end{aligned}$$

The case $\Delta\psi = 0$ determines the modification of the cavity mode wavelength at the incidence angle of θ. According to (7), we have

$$\Delta\lambda = -\frac{D^{\theta}\lambda_0}{2D^{\lambda}}\sin^2(\theta) \quad (8)$$

which clearly shows that the modification of the cavity mode wavelength is proportional to $\sin^2(\theta)$ and the larger the angle of incidence, the shorter the resonant wavelength.

Fig. 1 shows the resonant wavelength of the TPA microcavity as a function of incident angle. The resonant wavelength at normal incidence for this device was 1.512 μm. By rotating the TPA microcavity by an angle θ, the resonant wavelength changes, in accordance with (8). The agreement between (8) and the experimental results is excellent for θ up to 45°. A tuning range of 35 nm is achieved by rotating the TPA microcavity over 45°. Angle tuning beyond 45° is possible but we were limited to 45° by the range of our rotation stage. Extrapolating these results to a DWDM system a TPA microcavity with a normal incidence resonance at 1565 nm would, therefore, be able to scan over the entire C-band (1530–1565 nm) for an angular range of 45°. In a potential 160-Gb/s system, the 2-ps pulsewidth will result in 5-nm spacing between channels to prevent crosstalk. Thus, the microcavity structure would allow seven channels to be monitored with the same detector. In a customized setup tuning over 60° would certainly be possible corresponding to a channel selection bandwidth of 55 nm. This would, for instance, allow for tuning into the L-band beyond 1570 nm. Again with a channel spacing of about 5 nm, this would allow for approximately 11 channels with 2-ps pulses at 160 Gb/s to be monitored.

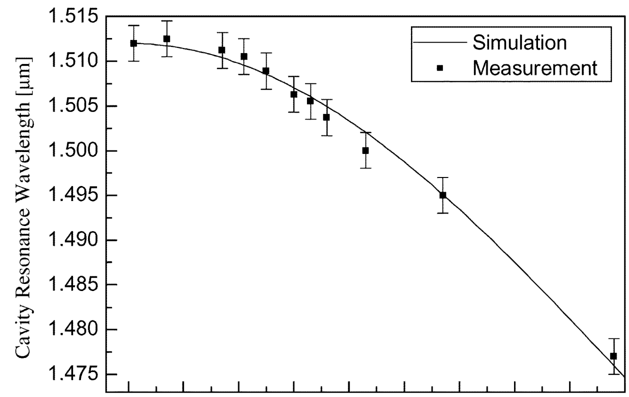

Fig. 1. Peak TPA response wavelength of the microcavity versus the incident angle, measurement, and simulation. Cavity resonance at normal incident is 1512 nm.

For the factor F in (1), we can make the following approximation by using (7):

$$F \approx [(1-R)^2 + R\Delta\psi^2]^{-1} = R \times \left\{\left(\frac{1-R}{\sqrt{R}}\right)^2 + \left[\frac{4\pi D^{\lambda}}{\lambda_0^2}\Delta\lambda + \frac{2\pi D^{\theta}}{\lambda_0}\sin^2(\theta)\right]^2\right\}^{-1}. \quad (9)$$

It can be seen that F has a Lorentzian lineshape if $\Delta\lambda$ or $\sin^2(\theta)$ is taken as the argument. Under the condition of normal incidence but varying the incident wavelength, F as a function of λ has a full-width at half-maximum (FWHM) of

$$\lambda_{\mathrm{FWHM}} = \frac{1-R}{\sqrt{R}}\frac{\lambda_0^2}{2\pi D^{\lambda}} \quad (10)$$

which is just the linewidth of the cavity reflection or transmission spectrum. If the incident wavelength is kept as λ_0 but the incident angle increases, F as a function of $\sin^2(\theta)$ has an FWHM of

$$[\sin^2(\theta)]_{\mathrm{FWHM}} = \frac{1-R}{\sqrt{R}}\frac{\lambda_0}{\pi D^{\theta}} = \frac{2D^{\lambda}}{D^{\theta}\lambda_0}\lambda_{\mathrm{FWHM}}. \quad (11)$$

The formula shows that the angle dependence is connected to the cavity bandwidth. This dependence is shown in Fig. 2, the TPA response decreases with increasing angle, and the FWHM of the angular response of the TPA device for a constant wavelength λ_0

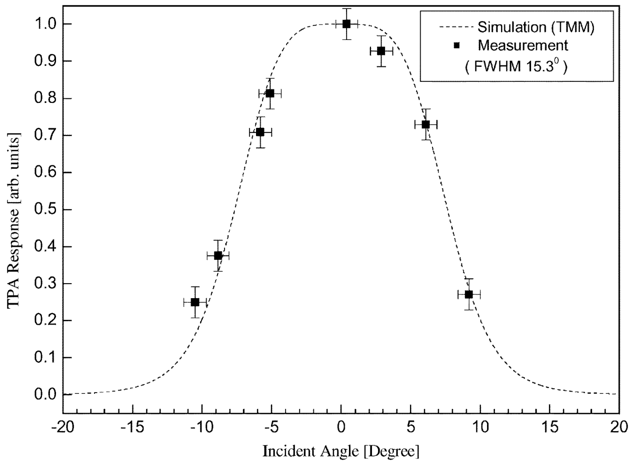

Fig. 2. Simulated and measured results for the TPA response at fixed resonance wavelength as a function of angle. If normally incident, the resonance wavelength is 1512 nm and the FWHM of the reflectivity spectrum is 4 nm.

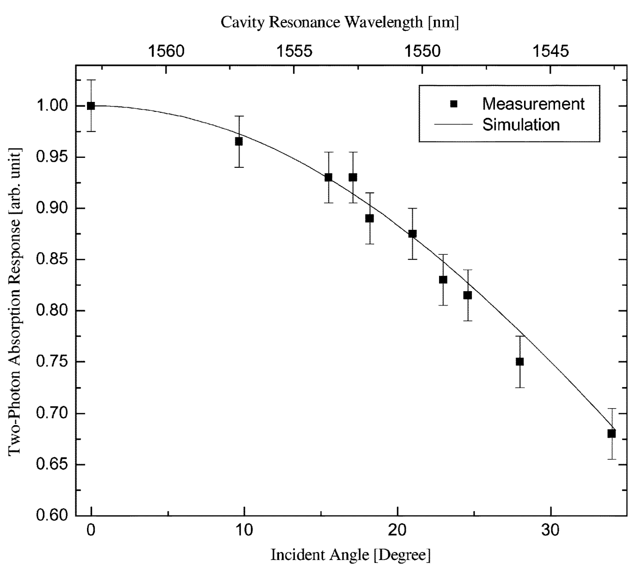

Fig. 3. Peak TPA response as a function of cavity resonance wavelength and incident angle. Cavity resonance at normal incidence is 1566 nm.

is 15.3°. These analytic results agree well with the simulations based on plane waves using the full TMM approach. From (1), it can also be seen that the TPA inside the cavity is dependent on F squared, e.g., if F drops to $1/\sqrt{2}\,F$, the corresponding width is 64% of its original value given by (10). Fig. 3 shows the dependence of the peak TPA response at the resonance wavelength on the tuning angle. Here a different sample has been used with a cavity resonance for normal incident of 1566 nm. The TPA response at cavity resonance frequency for an incident angle of 45° should be half that of the TPA response at normal incident. This is expected from (1), which indicates that if the resonance conditions are always satisfied as the incident angle increases, i.e., $\Delta\psi = 0$, the TPA will drop as $\cos^2(\theta)$. The measured electronic signals for different wavelengths in a multichannel WDM system could be accordingly amplified and/or normalized for further analysis as the $\cos^2(\theta)$ functional variation is straightforward. Experimental data at angles greater than 35° is not available due to mode hopping in the source laser below 1540 nm. Excellent agreement between the predicted and measured values is obtained over the 35° range which could be measured.

IV. Conclusion

We have demonstrated the practicality of a TPA microcavity structure for pulse characterization measurements at a range of wavelengths. This form of pulse monitoring technique lends itself to convenient experimental implementation in DWDM. Since TPA is a nonphasematched process, pulse characterization can be performed over a wide wavelength range (>50 nm) with a single detector by simply exploiting the angular response of the microcavity.

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