Polarization-insensitive cross correlation using two-photon absorption in a silicon photodiode

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We present experimental measurements of the polarization dependence of two-photon absorption in silicon photodiodes at 1550 nm, and we offer a simple theory that explains our observations. Based on this theory, we propose and demonstrate that it is possible to construct an optical cross-correlation system that is polarization insensitive, provided that one of the two input polarization states can be controlled.

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Optical cross-correlation methods have been proposed for applications including optical sampling, address–pattern recognition, demultiplexing, and clock recovery. Many correlation techniques, such as sum-frequency generation in $\chi^{(2)}$ crystals, are polarization dependent, making them impractical in fiber-based systems. Two-photon absorption (TPA) in photodiodes[1–3] or waveguide detectors[4,5] has been widely investigated as a simple, inexpensive, ultrafast,[6] and ultrasensitive[7–9] alternative to sum-frequency generation. Although silicon photodiodes are often used for TPA, comparatively little attention has been devoted to polarization dependence in these devices, especially at the wavelengths used in telecommunication systems. In this Letter we explore the polarization sensitivity of TPA in silicon photodiodes at a wavelength of 1550 nm. We show that in cross-correlation measurements, by prescribing one of the input polarization states it is possible to produce a cross-correlation signal that is insensitive to the polarization of the second input signal.

Polarization dependence and anisotropy have been explored both theoretically and experimentally in GaAs and other direct bandgap semiconductors.[10–14] Most of the experimental measurements of polarization sensitivity involve transmission through bulk samples rather than direct measurement of the nonlinear photocurrent in a detector. Murayama and Nakayama[15] described a theoretical calculation of polarization dependence and anisotropy of TPA in silicon, but their models do not include the important wavelength range near 1550 nm.

Our work began with an empirical observation that, for a variety of silicon photodiodes, the photocurrent produced through TPA is the same for all linear polarizations,[7] but it decreases for circularly polarized signals, as shown in Fig. 1. These measurements were performed with a chopped cw input signal at a wavelength of 1550 nm focused onto a silicon avalanche photodiode (EG&G C30902E) connected to a lock-in amplifier. For the measurements shown in Fig. 1(a), the linear polarization state was varied by use of a polarizer followed by a rotatable half-wave plate, which resulted in very little change in the nonlinear photocurrent. When the polarization state was instead varied from linear to circular (by repeating the same measurement using a quarter-wave plate instead of a half-wave plate), we observed that the nonlinear photocurrent decreased by a factor of approximately 0.64 for circularly polarized signals, as shown in Fig. 1(b). This result is very close to the ratio of 2/3 expected for isotropic nonlinear materials.[16] The linear–circular dependence was found to not depend on the orientation of the linear polarization state (ϕ). We obtained similar results for two different p-i-n photodiodes (EG&G FND-100 and EG&G YAG-100). These measurements suggest that at a wavelength of 1550 nm the silicon photodetector behaves almost as an isotropic nonlinear material.

For isotropic $\chi^{(3)}$ materials that satisfy Kleinmann's symmetry, the photocurrent generated through TPA can be described by

$$i_{\mathrm{TPA}} \propto \langle |\mathbf{E}(t)|^4 \rangle, \tag{1}$$

where $\langle\cdot\rangle$ indicates the time average. We emphasize that the field $\mathbf{E}(t)$ appearing in expression (1) is a real-valued vector function of time, $|\cdot|$ is the magnitude of this vector, and the time average is taken over the rapid optical oscillations. Among other things,

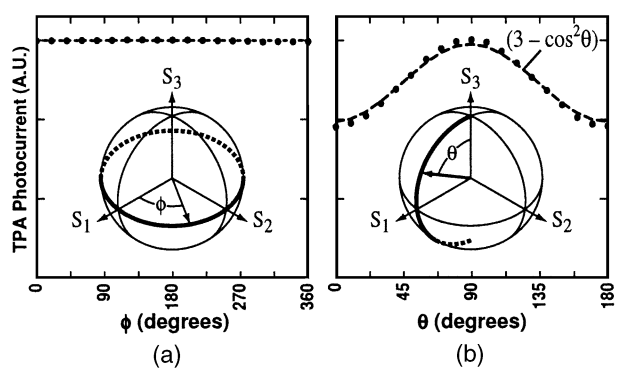

Fig. 1. Measured polarization dependence of TPA for a cw optical signal at 1550 nm (a) when the direction of linear polarization is adjusted and (b) when the polarization is adjusted from circular to linear. The insets depict the corresponding points on the Poincaré sphere for each of the plots.

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expression (1) predicts that, although the nonlinear photocurrent is the same for all linear polarizations, it decreases by 2/3 for circularly polarized signals of the same intensity, in agreement with our measurements. Given this nonintuitive polarization dependence, it is not obvious how the photocurrent will vary in cross-correlation systems, where there are two distinct input polarization states.

In cross-correlation measurements the averaged photocurrent $i_{\mathrm{TPA}}(\tau)$ consists of a background level B that is present even when the optical signals do not overlap, along with a cross-correlation signal of magnitude C, as shown schematically in Fig. 2. Both of these levels depend on the polarization states of the two input signals.

The simple model for polarization dependence given by expression (1) can be used to predict the form of the cross-correlation signal. To begin, suppose that the two input signals are described by scalar power envelopes $g(t)$ and $g'(t)$, respectively, and that both signals repeat with a period of T. We assume that both the repetition rate $1/T$ and the difference in optical carrier frequencies exceed the electrical bandwidth of the detector. Additionally, we assume that the polarization states of the two signals are described by normalized Stokes parameters $\mathbf{S} = (S_1, S_2, S_3)$ and $\mathbf{S}' = (S_1', S_2', S_3')$, which we initially regard as constants. Under these conditions, expression (1) predicts that the average photocurrent is

$$i_{\mathrm{TPA}}(\tau) = \eta\bigg[\langle g^2(t)\rangle\left(\frac{3}{8} - \frac{1}{8}S_3^{\,2}\right) + \langle g'^2(t)\rangle\left(\frac{3}{8} - \frac{1}{8}S_3'^{\,2}\right) + \langle g(t)g'(t-\tau)\rangle \times \left(1 + \frac{1}{2}S_1S_1' + \frac{1}{2}S_2S_2'\right)\bigg], \quad (2)$$

where η is a constant that depends on the material properties, focused spot size, and detector geometry. The first two terms in Eq. (2) represent the constant background level arising from each of the two signals, and the last term is proportional to the cross-correlation between power envelopes g and g'.

In the special case that envelopes g and g' are identical (but $\mathbf{S}$ and $\mathbf{S}'$ are not necessarily equal), Eq. (2) predicts that the background and cross-correlation amplitude shown in Fig. 2 are given by

$$B = K\left[\frac{3}{4} - \frac{1}{8}(S_3^{\,2} + S_3'^{\,2})\right], \quad (3)$$

$$C = K\left[1 + \frac{1}{2}(S_1S_1' + S_2S_2')\right], \quad (4)$$

where $K = \eta\langle g^2(t)\rangle$. One can verify that, in the special case $\mathbf{S} = \mathbf{S}'$, Eqs. (3) and (4) predict the familiar contrast ratio of 2:1 (C:B) expected for collinear fringe-averaged autocorrelation measurements.

Equation (3) predicts that the background level B can range from $K/2$ in the case of two circularly polarized signals to $3K/4$ for two linearly polarized signals. Provided that it does not change rapidly, background level B can be automatically removed by filtering,[3] chopping,[17] dithering, differential detection, or post-detection signal processing.[5] In addition to changes in the background, Eq. (4) predicts that the correlation magnitude C can vary from a minimum of $K/2$ for orthogonal linear polarizations to a maximum of $3K/2$ for parallel linear polarizations. Equation (2) reveals that this 3× variation in the cross-correlation term should be expected even in the more general case when the envelopes are not identical. Although it would be possible to eliminate this dependence by inserting a polarization-tracking or scrambling component at the input, such components introduce complexity, often consume signal power, and may not perform adequately when the input polarization state fluctuates rapidly.

In almost all applications, one of the optical signals is generated locally and can therefore have a prescribed polarization. One observes from Eq. (2) that, if one of the polarization states is circular (e.g., $S_1 = S_2 = 0$), the cross-correlation term will be independent of the other polarization state, $\mathbf{S}'$. In this case the size of the cross-correlation signal is reduced by only 33% compared with its maximum possible value.

Figure 3 shows the experiment used to verify this principle. Each of the two signals was generated by a tunable laser and a chirp-free electro-optic modulator, driven by a programmable pulse generator. The resulting rectangular pulses had a duration of 300 ns, peak power of 8 mW (measured at the detector), and a repetition rate of 1 MHz. The relative delay τ was varied electrically. A long-pass filter was used to reduce the effects of ambient light. The beam was focused to a spot size of approximately 3.5 μm (FWHM) onto the surface of a silicon avalanche photodiode

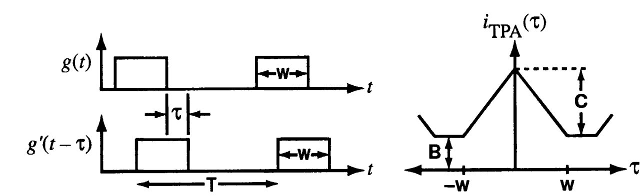

Fig. 2. Example of cross-correlation measurement. The averaged photocurrent comprises a background level B and a cross-correlation signal of height C, both of which depend on the input polarization states.

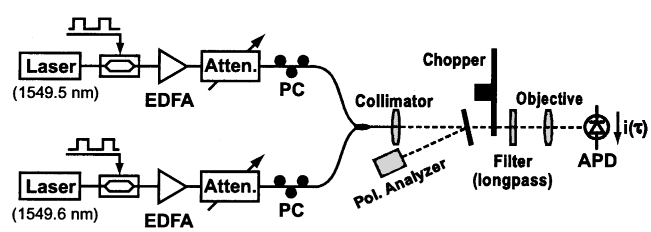

Fig. 3. Experimental setup used to investigate polarization sensitivity in cross-correlation measurements based on TPA. Each arm produces a train of 300-ns rectangular pulses with a peak power of 8 mW at the detector and a repetition rate of 1 MHz. The cross correlation is measured with a silicon avalanche photodiode (APD). PCs, polarization controllers; EDFAs, erbium-doped fiber amplifiers; Atten., attenuator.

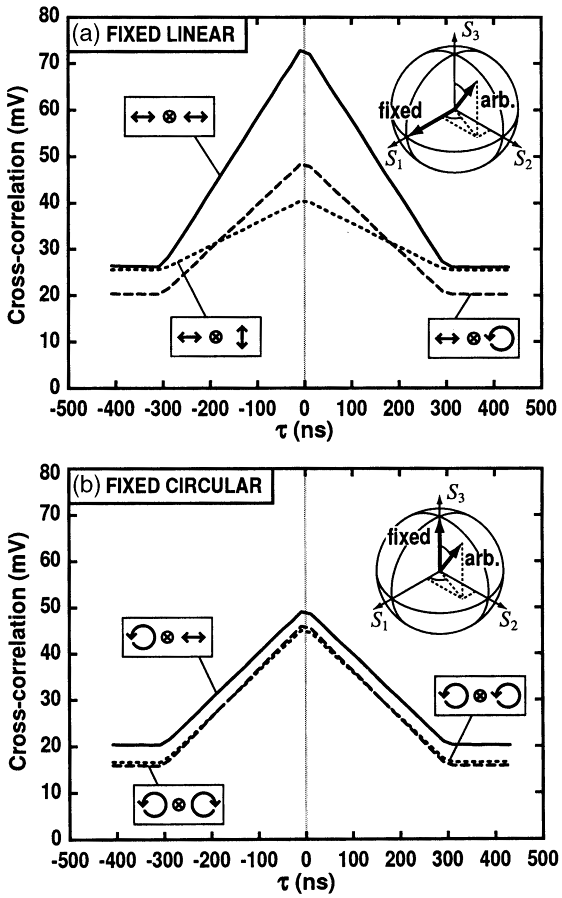

Fig. 4. Measured cross-correlation functions when the fixed input polarization state is (a) linear and (b) circular.

(EG&G C30902E). We used a chopper and a lock-in amplifier to improve the signal-to-noise ratio, but it is also possible to directly measure the nonlinear photocurrent on an oscilloscope. The removable near-normal incidence mirror redirects the beam to a polarization analyzer, which allowed us to control the polarization state of each input signal before the measurement by adjusting the fiber polarization controllers.

As shown in Fig. 4(a), when one of the signals has a fixed linear polarization, the cross-correlation magnitude C varies by a factor of $\sim 3\times$, with the largest correlation occurring for copolarized linear states and the smallest correlation occurring for orthogonally polarized linear states. Figure 4(b) shows that when one of the signals instead has a fixed circular polarization, the cross-correlation signal is invariant to the second polarization state, and the background level changes by only 25%. These results agree with the simple theory presented above. For the more general case when the uncontrolled polarization state is elliptical, we have confirmed that the cross-correlation curve falls between the two extremes plotted in Fig. 4(b) and that variations in the polarization state cause only the background level to change.

Because of experimental limitations, our measurements were performed with relatively long pulses, however, others have recently used TPA in silicon photodiodes to measure 20-fs pulses,[6] which suggests that our technique could be readily scaled to much higher speeds.

In summary, we have presented a simple theory that accurately predicts the polarization dependence of two-photon absorption at 1550 nm in silicon photodiodes. We apply the theory to predict the polarization dependence of TPA in cross-correlation measurements, and we confirm experimentally that, when one of the polarization states is chosen to be circular, the cross-correlation signal is insensitive to the second polarization state.

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