Plasmonic enhanced two-photon absorption in silicon photodetectors for optical correlators in the near-infrared

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A high-density array of plasmonic coaxial nanoantennas is used to enhance the two-photon absorption (TPA) process in a conventional silicon photodetector from a mode-locked 76 MHz Ti:sapphire laser over a spectral range from 1340 to 1550 nm. This enhanced TPA was used to generate an interferometric autocorrelation trace of a 150 fs laser pulse. Unlike second-harmonic generation, this technique does not require phase matching or a bulky crystal and can be used on a low-cost integrated silicon platform over a wide range of near-IR wavelengths compatible with modern commercial tunable femtosecond sources. © 2016 Optical Society of America

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Measuring optical correlation via a nonlinear process is the primary method by which optical events on the femtosecond and picosecond scale are characterized. Typically, this correlation is achieved by second-harmonic generation in a crystal with a strong $\chi^{(2)}$ nonlinearity [1,2]. There are several notable disadvantages of this approach; it requires phase matching within the nonlinear crystal and, even when phase matching is achieved, it is highly susceptible to temperature deviation; a shift in ambient temperature by a few degrees can reduce the conversion efficiency by 10 dB or more [2]. Then, too, the crystals themselves are both bulky and costly. To overcome such limitations, correlators based on a two-photon-induced photocurrent in a photodiode has been developed. Like second-harmonic generation, two-photon absorption (TPA) is a nonlinear process and can be used for optical correlation. In a semiconductor, photocurrent is generated primarily by exciting charge carriers with photons of energy greater than that of the bandgap in a process of direct absorption. In silicon, for example, the bandgap is 1.14 eV, meaning that single-photon absorption can only occur for photons of wavelengths at or below approximately 1050 nm. Beyond this wavelength range, the detector operates in a nonlinear TPA regime.

One of the earliest demonstrations of two-photon-induced optical correlation used metal-semiconductor-metal structures on ZnSe and Cd$_{0.5}$Se$_{0.5}$ [3,4]. These, however, are limited to a spectral window between 480 and 950 nm wavelengths due to the 2.6 eV room temperature bandgap of ZnSe. Other two-photon photodetector schemes have been demonstrated in the near-infrared with GaAs, InGaAsP, and Si; these, however, are limited by low responsivity, on the order of $10^{-7}$ A/W, which limits their practical use for optical correlation [5–8]. Modern tunable femtosecond laser sources can generate ultrafast pulses from the visible through the near-infrared and telecom wavelengths, and up through 2.2 $\mu$m [9]. The applications of ultrafast optics at telecom wavelengths for both interconnects and integrated photonics are often cited and readily apparent. For these reasons, a low-cost correlator on an integrable platform, such as silicon, operating in the longer near-infrared wavelengths, is imminently useful. In this Letter, we use large high-density arrays of broadband plasmonic nanoantennas fabricated directly on bulk silicon photodetectors to localize the incident electromagnetic field in bulk silicon to enhance the generation of carriers by TPA. This allows for the realization of compact and low-cost optical correlators for femtosecond pulses in the near-infrared spectral range. While the results presented here will be primarily at telecom frequencies for silicon photodetectors, the techniques themselves are applicable for operation with two photons of radiation from any spectral range with an appropriate bandgap of the semiconductor detector.

The enhancement of two-photon processes using plasmonic nanoantennas has had numerous leading edge applications, including entangled TPA [10], high-performance silicon nanowire phototransistors [11], in vitro two-photon luminescence imaging of cancer cells [12], and the broadband enhancement of the two-photon emission from semiconductors [13]. In ultrafast optics, plasmonic nanoantennas have been used for a variety of applications, including ultrafast hotspot switching and pulse shaping [14], as well as multi-photon photoluminescence [15]. TPA is a nonlinear process; for degenerate TPA, the
rate of TPA depends approximately on the square of the intensity of incident light or, alternatively, as $|E|^4$ [16,17], where $E$ is the amplitude of the optical field. When operating beyond the single-photon absorption regime of a photodetector, as defined by its bandgap, the measured photocurrent will be the result of a TPA process in the semiconductor. In the case of two delayed optical pulses that have spatial and temporal overlap, the two-photon-induced photocurrent in the semiconductor becomes a measure of the autocorrelation signal of a pulse with itself given by

$$S(t) = 2 \int_{-\infty}^{\infty} I(t)I(t+\tau)d\tau + 4 \text{Re}[F_1(t)e^{-i\omega \tau}] + \text{Re}[F_2(t)e^{-2i\omega \tau}],$$

where $I(t)$ represents the intensity of the original pulse, $I(t+\tau)$ represents the temporally delayed pulse, and $F_1, F_2$ are interference terms that can be filtered or avoided in a non-collinear geometry [5]. A typical plasmonic nanoantenna may localize the incident electromagnetic field described by an amplitude enhancement factor on the order of $10^2$. The corresponding increase in the TPA rate would then be on the order of $10^8$. Of course, we do not expect this enhancement to permeate through the full 2 μm absorption layer of a typical silicon photodiode [6]; rather, we expect this extremely strong effect to be present near the surface within 50 nm of the coaxial nanoantenna array, with no enhanced TPA beyond a 100 nm depth.

By etching the nanoantennas into the detector itself, either in a CMOS process or in post-process fabrication, one could conceivably permeate the entire absorption layer of a photodiode. In this Letter, however, we will use a low-cost lift-off fabrication technique to construct the nanoantenna array directly on the surface of the silicon photodetector. Furthermore, the measured results of enhancement in TPA and autocorrelation are used to demonstrate the feasibility of this approach.

To realize two-photon enhancements, an array of gold coaxial nanoantennas [18] with spectrally broadband resonances centered within the telecommunication spectrum bands were fabricated on top of a silicon photodetector. The antennas [see Fig. 1(a)] are 400 nm in diameter fabricated in a two-dimensional array with a lattice constant of 800 nm [see Fig. 1(b)]. Lithography was performed on a 100 nm layer of PMMA deposited on a photosensitive silicon photodetector (Edmund Optics 84-997) using a Vistec EBPG5200 electron beam writer at a dosage of 800 μC/cm². The full nanoantenna array has dimensions of 1 × 1 mm. The nanoantenna material stack consists of a 30 nm layer of Au on top of a 3 nm adhesion layer of Cr. While the coaxial geometry of the nanoantennas provides some localization within the ring, most of the localization occurs in the gap between the internal prongs and the core of the antenna; in effect, this gap size represents a critical dimension for a plasmonic nanoantenna. It is in this gap that we measure the amplitude enhancement, defined as the magnitude of the optical field amplitude in the gap over that of the incident optical field; i.e., $|E|/|E_o|$. A detailed analysis of this coaxial nanostructure, including its spectral and polarization response, is available in [18]. Approximately 1.56 million nanoantennas were fabricated on the surface of the commercially available photodetector over a 1 mm² area [see Fig. 2(a)].

Owing to the large write area, variations in the beam current, surface defects, and variations in the resist profile, the nanoantennas experienced variation in critical dimensions across the entire array. Most notably, the gap size of 367 nanoantennas sampled from different parts of the array varied from 10 nm to approximately 40 nm. The spectral dependence of the amplitude enhancement factor for coaxial nanoantennas with gaps ranging from 10 to 40 nm were simulated using the finite element method and is shown in Fig. 1(c). It is evident that the localization from this particular coaxial geometry has demonstrated resilience toward large fluctuations in gap size with an amplitude enhancement factor well above $10^2$ on the tip of the prongs, even with gaps as large as 40 nm [18].

The responsivity of the photodetector was characterized, with a photocurrent as a function of incident mean power from a Ti:sapphire laser focused down to a spot of 1 mm diameter at $\lambda = 1340$, $\lambda = 1400$, and $\lambda = 1550$ nm, as shown in Figs. 3(a)–3(c), respectively. For comparison, these measurements were performed on a 1 mm² area of bare surface on the Si photodiode and on a 1 mm² area of the Si photodiode covered by the nanoantenna array.

The photocurrent increase, $\Delta I$, in the nanoantenna array with respect to the bare surface is shown in Fig. 3(d). $\Delta I$ is greatest across all levels of incident optical power for
\[ \lambda = 1340 \text{ nm} \], which is consistent with a slightly higher localization in the spectral response of the nanoantennas in that spectral region, as shown in Fig. 1(c). From Fig. 3, it is clear that the nanoantenna array increases the TPA responsivity of the photodetector significantly. From Fig. 3, we observe that the nanoantenna array on the surface of the Si photodetector increased the TPA-induced peak photocurrent generation by factors of 2.77, 2.97, and 3.07 at the wavelengths of 1340, 1400, and 1550 nm, respectively.

We also performed an interferometric autocorrelation measurement at a wavelength of \( \lambda = 1320 \text{ nm} \) for sech\(^2\) pulses generated from a mode-locked Ti:sapphire laser. For comparison, the autocorrelation was measured using a Michelson interferometer for both second-harmonic generation in a beta barium borate (BBO) crystal and TPA in a nanoantenna enhanced silicon photodetector. The BBO output signal was measured with a PDA55 photodetector. Both measurements were completed using similar optical setups, the principal differences being that the second-harmonic generation measurement required additional optics for focusing and phase matching in the BBO crystal, as well as the PDA55 detector for measuring the output signal with two additional two short-pass filters (Thorlabs FESH0850) in front of the detector to reject the residual pump, as shown in Fig. 2(b); the nanoantenna enhanced TPA autocorrelation measurement did not require these additional components. The intensity of both the second-harmonic generation signal and the TPA signal, as a function of delay line position, are shown in Fig. 4. The experimental configuration for the TPA autocorrelation measurement is shown in Fig. 2. Both results were consistent with a 150 fs sech\(^2\) pulse and consistent with each other (Fig. 4).

![Fig. 2.](image)

![Fig. 3.](image)

![Fig. 4.](image)
These enhancements were achieved with 30 nm thick nanoantennas on the surface of a detector; if metal structures were fabricated within the detector itself, e.g., using aluminum in the metallization step of a CMOS process in-foundry, it is probable that a significantly greater enhancement could be achieved due to a greater overlap in the interaction cross section of the nanoantenna localization and the carriers within the doped silicon.

In conclusion, we demonstrated enhanced TPA in a silicon photodetector using a large array of coaxial nanoantennas on the chip surface. This enhanced TPA was used as the basis for realizing a compact, low-cost autocorrelator. This approach to optical correlation can be generalized to apply to the TPA band of any semiconductor detector. While the results presented here consisted only of enhanced TPA near the surface of the detector, in the future this approach may be further refined by integrating it with the metallization process of a CMOS foundry, allowing extension of the antennas through the entire 2 µm absorption layer of a semiconductor photodetector. Such a process could potentially be used to develop a fully integrated optical correlator on a chip.

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