Ultrasensitive and high-dynamic-range two-photon absorption in a GaAs photomultiplier tube

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We demonstrate improved efficiency and dynamic range for two-photon absorption at 1.5 μm in a photoelectron-counting GaAs photomultiplier tube. cw laser measurements show pure two-photon absorption occurring in the device from average powers of 1.3 μW to nearly 1 mW. We use the detector to implement an autocorrelator with peak-power × average-power sensitivity of 1.7×10^{-4} (mW)^2 and discuss practical ways to reduce this figure of merit to as low as 1×10^{-5} (mW)^2. © 2002 Optical Society of America

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Nonlinear absorption via $\chi^{(3)}$ in semiconductors generates a photoresponse that is quadratic with intensity. Such two-photon absorption exhibits several features that make it attractive for pulse characterization. First, the process can be observed with low-intensity signals. Second, the transitions are instantaneous and virtual, so phase matching is not required, enabling the process to work over a wide bandwidth. Third, each two-photon transition produces a carrier or photoelectron within the semiconductor that can be measured by simple direct electrical detection. Finally, compared with second-harmonic generation, two-photon absorption exhibits less polarization sensitivity because it is primarily an energy transfer process.

The features cited above make two-photon absorption an attractive alternative to the conventional approach to obtaining a quadratic nonlinearity in which sum-frequency light is generated in a nonlinear crystal and externally detected. Clear advantages exist for autocorrelation measurements with this process; however, it is also important to consider how two-photon absorption relates practically to the needs of light-wave communications systems at 1.5 μm for peak power detection and optical sampling, especially at both low average powers (~0.01 mW) and low peak powers (~0.1 mW). Considerable research on two-photon absorption near 1.5 μm in several devices, including silicon avalanche[1] and nonavalanche[2] photodiodes, InGaAsP lasers,[3] and GaAs quantum-well waveguides,[4] has been reported. These devices typically require high-input cw powers above 1 mW and peak powers above 1 W, or cw intensities in excess of 1 kW/cm^2, to generate two-photon absorption. Recent research with a photon-counting silicon avalanche photodiode extended the sensitivity to what we believe are the lowest cw powers reported to date at 1.5 μm of 100 μW, or 130 W/cm^2,[5] without the use of lock-in detection. All the devices mentioned above exhibit some residual single-photon absorption at low powers, which limits the sensitivity and dynamic range.

In this Letter we report our use of a GaAs photomultiplier tube (PMT) with low (<0.01-mW) average powers in combination with low (<0.1 mW) peak powers to generate two-photon absorption at 1.5 μm. This device distinguishes itself from others in that no single-photon absorption occurs, thereby allowing us to measure the two-photon response of extremely weak cw powers over nearly 5 orders of response magnitude, corresponding to powers ranging from 1.3 μW to nearly 1 mW. The PMT shows excellent potential for optically characterizing high-duty-cycle, high-repetition-rate data signals with extremely low peak and average power, as we demonstrate in autocorrelation measurements.

First we measured the nonlinear absorption characteristics of cw light in a GaAs photon-counting PMT (Hamamatsu Model H7421-50), using the configuration shown in Fig. 1(a). Light from a distributed-feedback (DFB) laser operating at a wavelength of 1545 nm was focused through an objective lens onto a photocathode, and the photoelectron count rate was measured as a function of the input power. The physical design of the PMT, depicted in the inset of Fig. 1(a), requires the use of a long-working-distance (>10-mm) objective to focus into the photocathode. The large, 5-mm photocathode diameter greatly facilitates alignment into the device because the transverse direction does not have to be accurately positioned. We used a Mitutoyu M Plan APO 20×, 0.42-N.A. objective lens to focus the light into the detector. The spot size was measured with this lens to be approximately 2 μm in free space, but we believe that the spot size at the photocathode is significantly larger owing to spurious reflections and aberrations within the PMT, which is not designed to accept such tightly focused beams. A long-wave-pass filter (LWPF) with a cut-on wavelength of 1300 nm eliminates stray photons that have sufficient energy to excite single-photon absorption, which would otherwise obscure the two-photon absorption.

GaAs exhibits an extremely sharp roll-off in the linear absorption at longer wavelengths beyond

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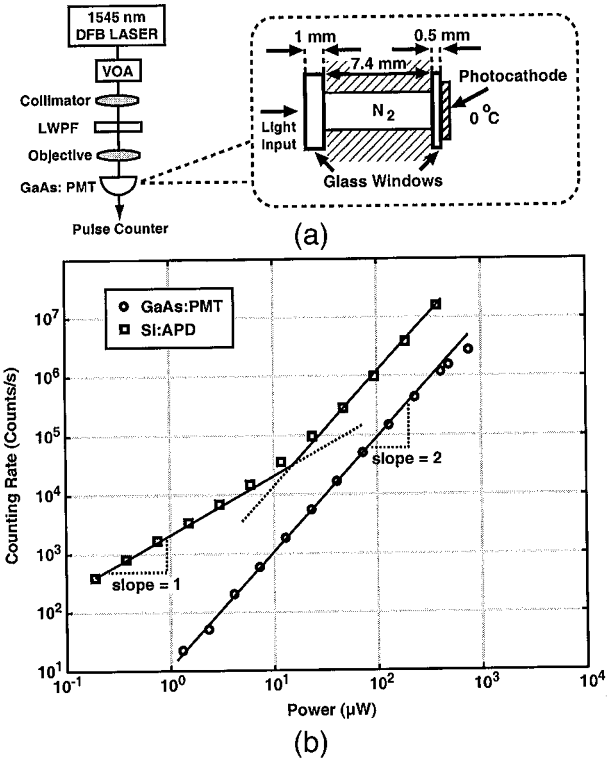

Fig. 1. (a) cw two-photon absorption measurement setup: VOA, variable optical attenuator. (b) cw response of the PMT and the photon-counting Si:APD after Ref. 5 (b).

the peak at 810 nm, and the direct bandgap contributes to a high two-photon absorption coefficient $\beta_2 \sim 20$ cm/GW. These features, combined with the extremely high internal gain of $\sim 10^7$ for this PMT, make this device an attractive candidate for two-photon absorption applications. Figure 1(b) shows the cw two-photon absorption response of the PMT in comparison with the silicon avalanche photodiode (Si:APD), after Ref. 5. The observed data clearly show a slope of two decades of photoresponse per decade of input optical power, as expected for two-photon absorption. The GaAs PMT exhibits two-photon absorption over nearly 5 orders of magnitude in response, limited on the low side by dark counts and on the high side by the maximum electronic counting rate. By contrast, the Si:APD is dominated by linear absorption at low power, which limits its dynamic range to less than 2 orders of magnitude. We attribute the behavior in silicon to the substantial absorption tail beyond 1.1 μm and to the lower β_2 of 1.5 cm/GW. The lower quantum efficiency ($\sim$15% of 810 nm) of the GaAs PMT compared with the Si:APD ($\sim$70% at 1.0 μm) leads to fewer counts; however, the advantages in dynamic range increase the usefulness of the device for low-average-power and low-peak-power pulses.

Previous studies have explored two-photon absorption in photomultiplier tubes. Two-photon absorption autocorrelation was first demonstrated at 515 nm by use of a molybdenum PMT.[6] Other devices explored have comprised Cs–Sb (Ref. 7) and Cs–I (Ref. 8); however, these experiments have all been confined to shorter wavelengths, exhibited less dynamic range, and required much higher average and peak powers, of $\sim$1 mW and $\sim$100 W, respectively. An additional attractive feature of the GaAs PMT studied here results from the operability of this device at 1.5 μm. According to theory, the peak in β_2 occurs at photon energies near 0.7 times the bandgap energy, which for GaAs is close to 1.5 μm.[9]

To demonstrate the usefulness of the PMT for pulse characterization at 1.5 μm we implemented an interferometric autocorrelator, using the PMT device as illustrated in Fig. 2. The setup uses a standard collinear Michelson configuration, which enables fringe-resolved measurements to be made. A 10-GHz mode-locked fiber laser is used to generate 1.56-ps pulses with the optical spectrum shown in the inset of Fig. 3(b). Figure 3 reveals the measured autocorrelation for average optical powers of 6.4 and 2.3 μW incident upon the detector. The inset of Fig. 3(a) is an enlarged view of the interference fringes at the peak of the autocorrelation, showing the expected $\cos^4()$ fringe shape. The autocorrelation profile has a 2.6-ps full width at half-maximum, from which we infer a pulse width of 1.56 ps. We obtained the white curves in Fig. 3 by numerically low-pass filtering the interference fringes from the data, although we have verified that such intensity autocorrelations can also be obtained directly from our setup by increasing the scan speed or the count interval. These measurements demonstrate peak-power × average-power sensitivities of 1.3×10^{-3} (mW)^2 and 1.7×10^{-4} (mW)^2, respectively, without the use of synchronous photon counting or lock-in detection. Note additionally that the autocorrelation maintains the expected 8:1 peak-to-background ratio at the lowest power measured as a result of the absence of single-photon absorption. To our knowledge this performance for two-photon absorption has never before been observed at such low powers.

Based on the cw data in Fig. 1(b), we believe that it should be possible to improve the sensitivity further below 1×10^{-5} (mW)^2, or 2 orders of magnitude below previous demonstrations.[5] First, one could reduce the dark-count rate to 40 counts/s by cooling the device

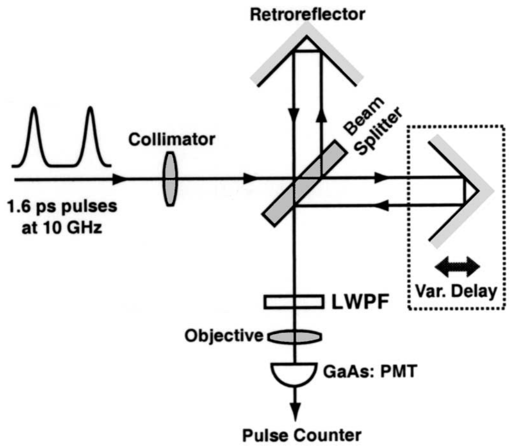

Fig. 2. Interferometric autocorrelator setup.

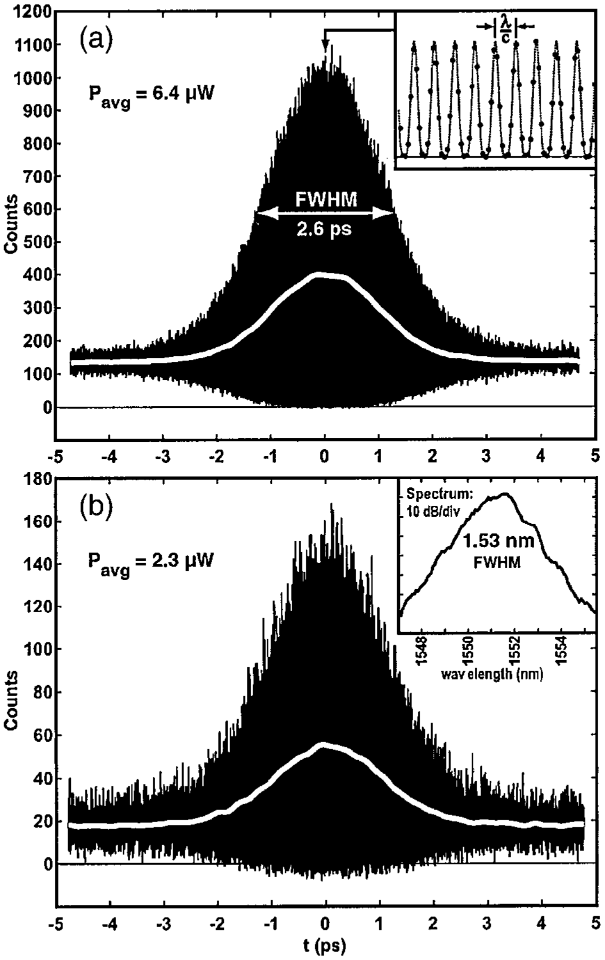

Fig. 3. Autocorrelation of a 10-GHz, 1.56-ps pulse train at average powers of (a) 6.4 and (b) 2.3 μW with dark counts subtracted out. Insets: (a) interference fringes and (b) corresponding 1.53-nm FWHM optical spectrum.

to −10 °C. Second, two-photon absorption can be enhanced by focusing more efficiently into the photocathode, and the response increases quadratically with inverse spot area. However, the minimum spot size in our current experiments is limited by aberrations and reflections off the windows and GaAs photocathode surfaces diagrammed in Fig. 1(a). Based on cw measurements with different lenses, we estimate the smallest obtainable spot size to be 5.2 μm at the photocathode, but by redesigning the PMT to allow for a shorter working distance, adding appropriate antireflection coatings, and optimizing focusing lenses it should be possible to reduce the spot size to the diffraction limit and obtain another order of magnitude improvement in the sensitivity. Finally, by using photocurrent detection at high signal levels instead of photoelectron counting, which suffers from saturation owing to electronic pulse overlap in the counting circuitry, the dynamic range could be extended to cover 6–7 orders of magnitude.

In summary, we have shown, for the first time to our knowledge, an unprecedented combination of high sensitivity and wide dynamic range in a two-photon absorption process obtained with a GaAs PMT. The device shows a remarkable absence of the single-photon absorption that imposes a major limitation on other implementations. With this device we observed two-photon absorption at 1.5 μm over 5 orders of magnitude, extending to record low cw powers of 1.3 μW. We used the device to demonstrate an autocorrelator with a remarkable sensitivity of 1.7×10^{-4} (mW)^2, and we suggested simple ways to further reduce the sensitivity.

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