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On-chip autocorrelator using counter-propagating slow light in a photonic crystal with two-photon absorption photodiodes: supplementary material

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This document provides supplementary information to "On-chip autocorrelator using counter-propagating slow light in a photonic crystal with two-photon absorption photodiodes," https://doi.org/10.1364/optica.4.001109. Here, we describe the theoretical expression and calculation of the correlation waveform obtained in our autocorrelator, the structure and some properties of the device, and measurement setup.

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1. THEORETICAL EXPRESSION AND CALCULATION

By substituting Eq. (1) of the main manuscript into (2), $N(z)$ is obtained as follows:

$$N(z) \propto C_0 + C_1 \cos\left(2k\left(\frac{L}{2} - z\right)\right) + C_2 \cos\left(4k\left(\frac{L}{2} - z\right)\right) \quad \textbf{(S1)},$$

$$\begin{aligned} C_0 &= \int_{-\infty}^{\infty} I_1(z,t)^2 + 4I_1(z,t)I_2(z,t) + I_2(z,t)^2 dt, \\ C_1 &= 4\int_{-\infty}^{\infty} \sqrt{I_1(z,t)I_2(z,t)}\{I_1(z,t) + I_2(z,t)\}dt, \quad \textbf{(S2)} \\ C_2 &= 2\int_{-\infty}^{\infty} I_1(z,t)I_2(z,t)dt. \end{aligned}$$

Figure S1 shows each component of Eq. (S1). Regarding $C_0(z)$, the first and third terms in Eq. (S2) are the independent ones, which become the background, and the second term corresponds to the correlation. For a Gaussian pulse, the background is 0.333 when $C_0(z)$ is normalized. The second and third terms of Eq. (S1) are the fast oscillating functions, which disappear in the TPA-PDs by averaging.

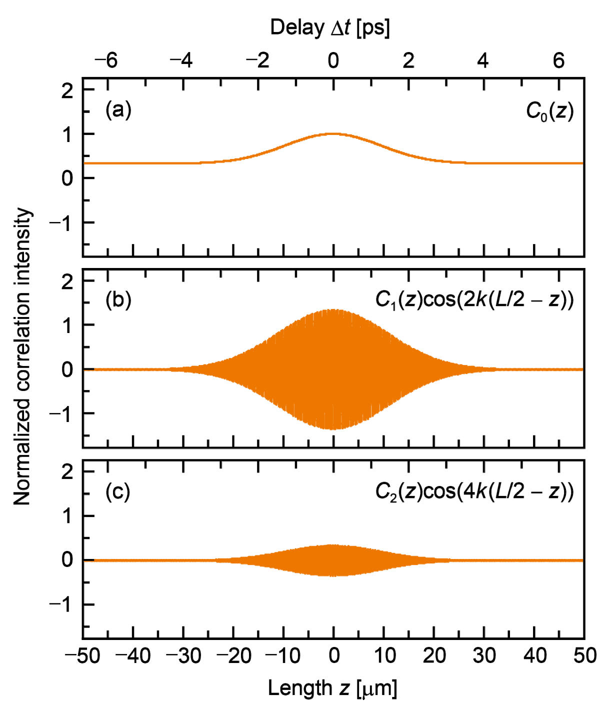

Fig. S1. Theoretical waveform of each component in Eq. (S2). (a) Envelope component. (b) and (c) Oscillating components. Full-width at half-maximum of pulse and n_g of LSPCW are set at 3 ps and 20, respectively.

2. DEVICE

The auto-correlator that comprises TPA-PDs embedded on the LSPCW was fabricated on a SOI wafer with 210-nm Si layer using a complementary metal oxide semiconductor process with KrF excimer exposure. All waveguides were cladded with SiO_2. The optical pulses were coupled from an external single mode fiber with a lens module into a spot-size converter with a coupling loss of 2.4 dB. This was followed by 400-nm-wide Si waveguides for optical wiring, which were locally expanded to 4 μm to suppress unwanted nonlinearity such as the optical Kerr effect. The pulses were split by a 50:50 multimode interference splitter with an excess loss of 0.23 dB [1] and then launched on the LSPCW from opposite ends with a coupling loss of 1.2 dB. Because the waveguide loss is negligible, the total loss of light from the fiber to each end of the LSPCW was 3.8 dB + 3.0 dB (for splitting). The length, lattice constant, hole diameter, and third-row lattice shifts of the LSPCW were set at 100 μm, 400 nm, 225 nm, and 90 nm, respectively, and the low-dispersion characteristics were obtained, as shown in Fig. 3(b). The p–n diode array of 3-μm length and 5-μm pitch was formed by boron-ion (concentration: 10.5×10^{17} cm^{-3}) and phosphorus-ion (6.2×10^{17} cm^{-3}) implantation. The propagation loss of the LSPCW was 220 dB/cm with doping and 10–20 dB/cm without doping. In each PD, the number of TPA-induced carriers was estimated from the responsivity characteristics in Fig. 3(c). For example, the 4.5-ps Gaussian pulse with a peak power of 3 W generated a photocurrent of 1 μA with a 40-MHz repetition, which corresponds to a charge generation of 25 fC/pulse. Considering the slab thickness of 210 nm and PD length of 3 μm and assuming that the depletion region was 0.3 μm wide under the reverse bias [2], the active volume was calculated to be 0.19 μm^3. Therefore, if the carrier lifetime is much longer than the pulse duration, the instantaneous carrier density in the depletion region is given as 8.2×10^{17} cm^{-3}. Because the background photocurrent is theoretically 0.333 times that of the correlation peak, as mentioned in Section 1, the background carrier density is 2.7×10^{17} cm^{-3}.

3. MEASUREMENT SETUP

Optical pulses from a mode-locked fiber laser with a repetition of 40 MHz were spectrally expanded via self-phase modulation in an erbium-doped fiber amplifier (EDFA). The spectrum was then filtered within a desired wavelength band using a programable liquid crystal on a Si filter (Santec Inc. WSS-1000), which filters with arbitrary spectrum shape and phase. Thanks to this filter, accurate Gaussian-shape pulses were generated. The input pulse width was varied by changing the filtering spectral width. The pulses were amplified using another EDFA again and their polarization was adjusted to transvers-electric using a polarization controller. Then, the pulses were incident on the device. The TPA-induced photocurrent from each PD was independently detected via Al electrodes and probes and measured using a picoammeter.

References

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