Supplementary Material

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Silicon photonic transmitter for polarization-encoded quantum key distribution: supplementary material

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This document provides supplementary information to "Silicon photonic transmitter for polarization-encoded quantum key distribution," http://dx.doi.org/10.1364/optica.3.001274. Details on the refractive index and absorption change as well as the electroluminescence in the forward-biased silicon (Si) PIN diodes are described.

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1. REAL AND IMAGINARY REFRACTIVE INDEX CHANGE IN SI WAVEGUIDE PIN DIODES

The modulation of the refractive index in silicon (Si) is typically through the plasma dispersion effect. The carrier density changes both the real and imaginary parts of the refractive index, which can cause, for example, a reduced extinction ratio in an optical attenuator or modulator, and polarization dependent loss in a polarization controller. According to [1], the changes in the refractive index Δn and absorption $\Delta\alpha$ of Si near a wavelength of 1550 nm are

$$\Delta n = -\left[8.8\times10^{-22}\Delta N_e + 8.5\times10^{-18}(\Delta N_h)^{0.8}\right], \quad \textbf{(S1a)}$$

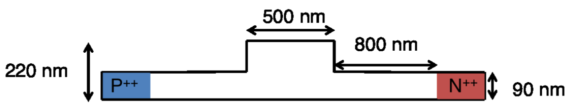
$$\Delta\alpha = 8.5\times10^{-18}\Delta N_e + 6.0\times10^{-18}\Delta N_h, \quad \textbf{(S1b)}$$

where ΔN_e and ΔN_h are changes in the free electron density and free hole density measured in cm^{-3}. By incorporating both Δn and $\Delta\alpha$ into a mode-solver, the coupled changes in the real and imaginary parts of the effective index as a function of carrier density can be modelled.

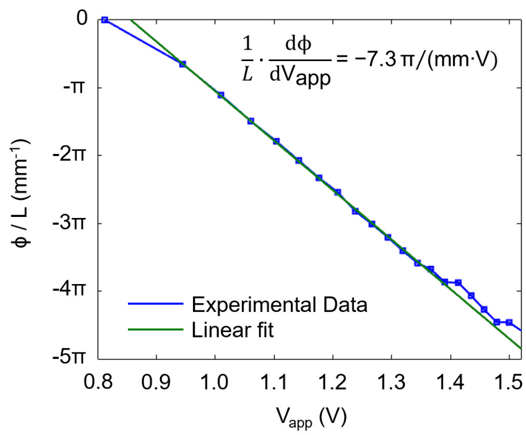
Experimentally, for the Si waveguide PIN diode with the cross-section illustrated in Fig. S1(a), which is similar to the one used in the present work, the measured phase-shift and attenuation as function of the applied forward bias voltage are shown in Fig. S1(b) and Fig. S1(c), respectively [2]. The length of the Si PIN diode used for these measurements was 500 μm. The measured differential phase-shift was about $-7.3\pi/(\mathrm{mm}\cdot\mathrm{V})$ and the corresponding differential absorption change was about 20 dB $/(\mathrm{mm}\cdot\mathrm{V})$. These figures have been reproduced from [2]. The Si PIN diodes we have used in the current work had P++ and N++ regions that were 700 nm away from the waveguide core compared to 800 nm in Fig. S1. The reduced separation would lead to a slightly lower series resistance.

2. ELECTROLUMINESCENCE FROM SI PIN DIODES

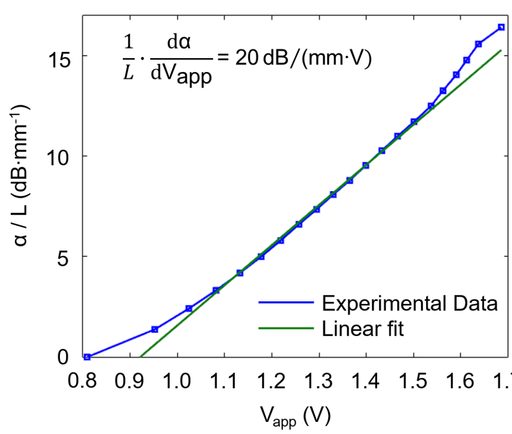
We observed that the Si waveguide PIN diodes in forward bias could generate weak electroluminescence. Fig. S2(a) shows the electroluminescence spectrum of a 1000 μm-long PIN diode at several forward bias voltages. The electroluminescence is broadband and centered near a wavelength of 1150 nm, close to the bandgap energy of Si (1.1 eV = 1130 nm). This electroluminescence is not power efficient due to the indirect bandgap of Si. Fig. S2(b) shows the current vs. voltage relationship of the diode. Fig. S2(c) shows the total optical power collected by a lensed single-mode fiber (matching the edge-coupler) as a function of the forward bias voltage. The electrical-to-optical power conversion efficiency is of the order of 10^{-7}%.



(a)

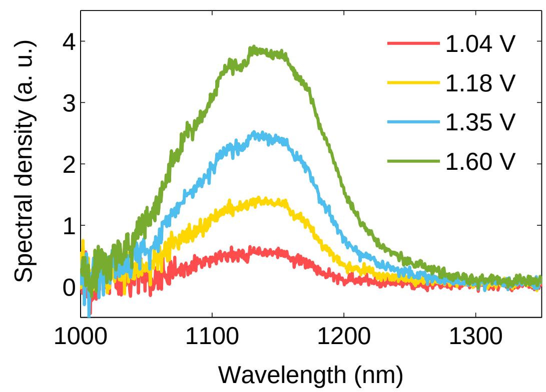


(b)

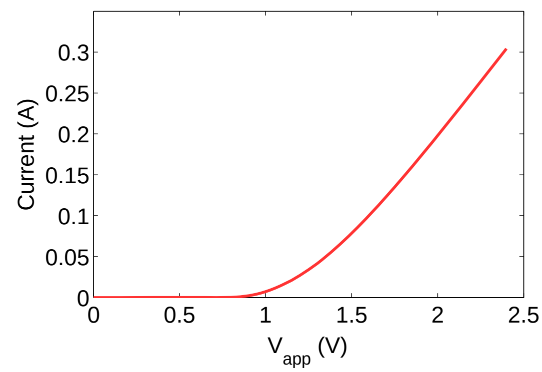


(c)

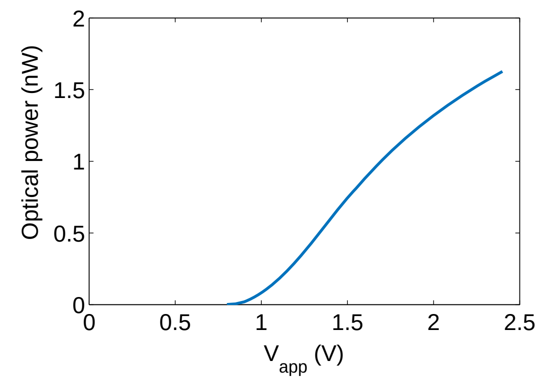
Fig. S1. (a) Cross-section of a Si rib waveguide PIN diode, and the corresponding (b) phase-shift and (c) attenuation as a function of the forward bias voltage applied to the Si PIN diode. L is the length of the Si PIN diode. Figures were reproduced from [2].



(a)



(b)



(c)

Fig. S2. (a) Electroluminescence from a 1000 μm-long Si PIN diode under several forward bias voltages. (b) Current vs. voltage curve of the Si PIN diode. (c) The collected optical power into a lensed single-mode fiber vs. forward bias voltage.

REFERENCES

1. R. A. Soref and B. R. Bennett, "Electrooptical effects in silicon," IEEE J. Quantum Electron. **23**, 123–129 (1987).
2. A. W. MacKay, "Complex phase biasing of silicon machzehnder interferometer modulators," Master's thesis, University of Toronto (2014).