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Control of the phase shift in a Mach-Zehnder interferometer with temperature via VO₂ phase transition and with light via pDTE photochromic switching

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Abstract: A simple control of the probability to detect a photon in a Mach-Zehnder interferometer has been herein demonstrated by exploiting the insulator/metal phase transition in VO₂ layers and by exploiting the photochromic switching in the polymer pDTE.

Re-programmable Mach-Zehnder interferometers are very important for photonic quantum technologies [1,2]. A Mach-Zehnder interferometer is used to measure the shift variation between two beams obtained by splitting light from a single source. A simple Mach-Zehnder interferometer consists of a light source, two 50/50 beam splitters, two mirrors, and two detectors. The beam of light from the source, which propagates in the x direction here, impinges the first beam splitter, giving rise to a beam directed in the x direction and one in the y direction. With two mirrors, the beams are deflected 90 degrees so that they rejoin at a second beam splitter. After the second beam splitter, one detector detects light in the x direction and the other detector detects light in the y direction. With a single photon source, the photon moving along the x axis is represented by the column vector $x=[1; 0]$, while the photon moving along the y axis is represented by the column vector $y=[0; 1]$. Mirrors are represented by the matrix $M=[1, 0; 0, 1]$, which beam splitters are represented by the matrix $BS=(1/\sqrt{2})*[1, i; i, 1]$ [3].

Vanadium dioxide layers are placed in the two arms of the Mach-Zehnder interferometer after the first beam splitter. The refractive index of such material is temperature dependent [4], due to a thermochromic phase transition. The layer of vanadium dioxide is represented by the matrix $VO_2=[\exp(i*2*\pi*d*n_x/\lambda), 0; 0, \exp(i*2*\pi*d*n_y/\lambda)]$, where d is the layer thickness, n_x is the refractive index for the layer in the x-direction, n_y is the refractive index for the layer in the y-direction, and λ is the wavelength. At 1200 nm, the refractive index of insulating VO₂ is $n_i=3.2278+0.4360i$, while the refractive index of metallic VO₂ is $n_m=1.7917+1.9732i$.

In a first gedankenexperiment, the two layers of VO₂, with a thickness of 208.9 nm, are both metallic or both insulating ($n_x=n_y$). Thus, the two arms of the Mach-Zehnder interferometer are balanced. To reach the detector in the x direction, the optical paths experience one reflection (one is transmitted by the first beam splitter and reflected by the second beam splitter, the other one is reflected by the first beam splitter and transmitted by the second beam splitter). To reach the detector in the y direction, one path is transmitted by the two beam splitters, while the other one is reflected by the two beam splitters: The two paths are out of phase by 180 degrees and destructively interfere. Thus, the photon is never detected at the detector in the y-direction [3]. In a second gedankenexperiment, the layer of VO₂, in the x direction after the first beam splitter, is in the insulating phase ($n_x=n_i$) and the layer of VO₂, in the y direction after the first beam splitter, is in the metallic phase ($n_y=n_m$). In such scenario, the probability to detect a photon for the detector in the x direction is 0.5 [i.e., $(\text{abs}(\text{transpose}(x)*BS*M*VO_2*BS*x))^2$], while the probability to detect a photon for the detector in the y direction is 0.5 [i.e., $(\text{abs}(\text{transpose}(y)*BS*M*BS*VO_2*x))^2$].

With two additional layers of a photochromic polymer, i.e., pDTE [5], with a thickness of 4777 nm, after the first beam splitter, a light-induced switching of the probability to detect a photon at the two detectors is possible. As for the VO₂ layer, the pDTE layer is represented by the matrix $pDTE = [\exp(i \cdot 2 \cdot \pi \cdot d \cdot n_x / \lambda), 0; 0, \exp(i \cdot 2 \cdot \pi \cdot d \cdot n_y / \lambda)]$. Upon UV irradiation, the polymer switches from a transparent phase, with $n_t = 1.5454$ at 1200 nm, to a blue phase, with $n_b = 1.6082$ at 1200 nm. In a third gedankenexperiment, the layer of pDTE, in the x-direction after the first beam splitter, is in the transparent phase ($n_x = n_t$) and the layer of pDTE, in the y-direction after the first beam splitter, is in the blue phase ($n_y = n_b$). In such scenario, the probability to detect a photon for the detector in the x direction is 0.5 [i.e., $(\text{abs}(\text{transpose}(x) \cdot BS \cdot M \cdot pDTE \cdot BS \cdot x))^2$], while the probability to detect a photon for the detector in the y direction is 0.5 [i.e., $(\text{abs}(\text{transpose}(y) \cdot BS \cdot M \cdot BS \cdot pDTE \cdot x))^2$].

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