Control of the phase shift in a Mach-Zehnder interferometer with temperature via VO_2 phase transition and with light via pDTE photochromic switching

Francesco Scotognella
Department of Applied Science and Technology, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
E-mail: francesco.scotognella@polito.it

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 VO_2 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/√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 VO2=[exp(i*2*π*d*nx/λ), 0; 0, exp(i*2*π*d*ny/λ)], where d is the layer thickness, nx is the refractive index for the layer in the x-direction, ny is the refractive index for the layer in the y-direction, and λ is the wavelength. At 1200 nm, the refractive index of insulating VO_2 is ni=3.2278+0.4360i, while the refractive index of metallic VO_2 is nm=1.7917+1.9732i.
In a first gedankenexperiment, the two layers of VO_2, with a thickness of 208.9 nm, are both metallic or both insulating (nx=ny). 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 VO_2, in the x direction after the first beam splitter, is in the insulating phase (nx=ni) and the layer of VO_2, in the y direction after the first beam splitter, is in the metallic phase (ny=nm). In such scenario, the probability to detect a photon for the detector in the x direction is 0.5 [i.e., (abs(transpose(x)*BS*M*VO2*BS*x))^2], while the probability to detect a photon for the detector in the y direction is 0.5 [i.e., (abs(transpose(y)*BS*M*BS*VO2*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 VO_2 layer, the pDTE layer is represented by the matrix pDTE=[exp(i*2*π*d*nx/λ), 0; 0, exp(i*2*π*d*ny/λ)]. Upon UV irradiation, the polymer switches from a transparent phase, with nt=1.5454 at 1200 nm, to a blue phase, with nb=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 (nx=nt) and the layer of pDTE, in the y-direction after the first beam splitter, is in the blue phase (ny=nb). In such scenario, the probability to detect a photon for the detector in the x direction is 0.5 [i.e., (abs(transpose(x)*BS*M*pDTE*BS*x))^2], while the probability to detect a photon for the detector in the y direction is 0.5 [i.e., (abs(transpose(y)*BS*M*BS*pDTE*x))^2].

References

[1] C.H. Bennett, Quantum cryptography using any two nonorthogonal states, Phys. Rev. Lett. 68 (1992) 3121–3124. https://doi.org/10.1103/PhysRevLett.68.3121.

[2] J. Wang, F. Sciarrino, A. Laing, M.G. Thompson, Integrated photonic quantum technologies, Nat. Photonics 14 (2020) 273–284. https://doi.org/10.1038/s41566-019-0532-1.

[3] F. Rioux, 8.86: Simulating a Quantum Computer with a Mach-Zehnder Interferometer, Chemistry LibreTexts (2019). https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Quantum_Tutorials_(Rioux)/08%3A_Quantum_Teleportation/8.86%3A_Simulating_a_Quantum_Computer_with_a_Mach-Zehnder_Interferometer (accessed February 27, 2024).

[4] R.M. Briggs, I.M. Pryce, H.A. Atwater, Compact silicon photonic waveguide modulator based on the vanadium dioxide metal-insulator phase transition, Optics Express 18 (2010) 11192–11201. https://doi.org/10.1364/OE.18.011192.

[5] C. Toccafondi, L. Occhi, O. Cavalleri, A. Penco, R. Castagna, A. Bianco, C. Bertarelli, D. Comoretto, M. Canepa, Photochromic and photomechanical responses of an amorphous diarylethene-based polymer: a spectroscopic ellipsometry investigation of ultrathin films, Journal of Materials Chemistry C 2 (2014) 4692–4698. https://doi.org/10.1039/C4TC00371C.