Mach–Zehnder–Fano interferometer
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Citation: Applied Physics Letters 95, 121109 (2009); doi: 10.1063/1.3232224
View online: http://dx.doi.org/10.1063/1.3232224
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The Mach–Zehnder interferometer (MZI) was suggested more than a hundred years ago, and it is still a key element in integrated optics being implemented into design of various photonic devices including modulators, switches, filters, and multiplexers. The recent developments moved this concept toward nanoscales, and several studies employed ring-resonator structures in order to lower the power threshold which can demonstrate very efficient nonlinear response and can be easily tuned. A novel advantage of using additional resonant cavities has been also discussed.

In this letter, we introduce a concept of the Mach–Zehnder–Fano interferometer that can be realized on various platforms such as photonic crystals or ring resonators that possess effective discreteness of periodic photonic structures for engineering the transmission properties. Side-coupled cavity with a resonant state in the transmission band provides a sharp variation of the scattering phase, which allows to alter the transmission properties of the whole structure in a narrow frequency range. Photonic crystals allow to implement this idea in the form of very compact structures.

The physics of the Fano resonance is explained by an interference between a continuum and discrete state. The simplest realization is a one-dimensional discrete array (continuum state) with a side-coupled defect (discrete state). In such a system, scattering waves can either bypass the defect or interact with it. The $\pi$ phase shift at the resonance results in destructive interference at the output, leading to resonant suppression of the transmission. Usually, each Fano resonance can be associated with a particular resonant state of the side-coupled defect. Similarly, we demonstrate below that MZI with a symmetric Fano defect displays a resonant state with a well-defined suppression of the transmission. However, for an asymmetric Fano defect, the transmission exhibits more than one resonance, and it can be understood in terms of the interaction between two continua with one discrete state. Indeed, both arms of MZI can be considered as two continua, and the side-coupled defect as a discrete state. Since both the arms are coupled, the defect becomes effectively coupled to both of them with different strengths. As a result, we may obtain two resonances instead of one. We introduce the main concept for an effective discrete model, and then apply it to photonic-crystal devices whose optical properties can be modeled by an effective discrete model derived by the Green’s function formalism.

First, we study the transmission properties of the MZI with a side-coupled Fano defect in a generic discrete model, as shown schematically in Fig. 1. We assume the nearest-neighbor interaction between the discrete sites. In all parts of the structure, the propagating waves can be separated onto forward and backward ones, and can be characterized by the corresponding amplitudes. The relation between the amplitude of the incoming and outgoing waves can be easily written in terms of the scattering-matrix approach,

$$
\begin{align*}
R & = S_Y^T \begin{pmatrix} A \end{pmatrix}, \\
C & = D_2, \\
T & = S_Y D_3 \begin{pmatrix} B \end{pmatrix},
\end{align*}
$$

with the scattering matrix of the Y-splitter of the form

$$
S_Y^K = \begin{pmatrix} e^{-2ikqY} & \frac{t_y}{e^{2ikqY}} & \frac{t_y}{e^{2ikqY}} \\
\frac{t_y}{e^{2ikqY}} & e^{2ikqY} & \frac{t_y}{e^{2ikqY}} \\
\frac{t_y}{e^{2ikqY}} & \frac{t_y}{e^{2ikqY}} & e^{2ikqY}
\end{pmatrix},
$$

where $K=L, -N$, while $t_y = 2/(3 - i\cot q)$ and $r_y = t_y - 1$ are the transmission and reflection amplitudes of the Y-splitter.

The relation between the scattering amplitudes of the lower arm with a side-coupled defect can be obtained via the transfer matrix

![Schematic structure of the Mach–Zehnder–Fano interferometer](image-url)
We consider the conventional MZI with the two symmetric arms of the same length. In the absence of a side-coupled defect (i.e., \(V_0 = 0\)), the transmission coefficient exhibits a periodic dependence, in analogy with the Fabry–Pérot resonance with zero phase difference at the output of both arms \(\Delta \phi = \phi_1 - \phi_2 = 0\), where \(\phi_1\) and \(\phi_2\) are the phases of the lower and upper arms of MZI, correspondingly. The number of peaks is proportional to the length of both the arms. In the geometry under consideration, the phase accumulation is linearly proportional to the length of the arms \(\phi_{1,2} \propto q(N-L)\). The purpose of our study is to demonstrate that, by adding a side-coupled defect, we may alter quite substantially this dependence due to presence of the Fano resonances. The main feature of the Fano resonance is suppression of the transmission. Side-coupled defect provides an additional resonant path. The scattering waves accumulate \(\pi\)-phase shift in the vicinity of a resonance. As a result, there is a sharp \(\pi\) jump of phase difference of scattered waves at the resonance, which leads to destructive interference and resonant suppression of the transmission. This strong dependence of the phase in the vicinity of the resonance will allow one to design the MZI with shorter arms, making the final device much more compact.

When a cavity is coupled to the straight waveguide, the Fano resonant reflection \((T=0)\) is observed at the eigenfrequency of the cavity mode, \(\omega_0 = E_F\). In the case of the MZI, it is no longer true. Indeed, by attaching the Fano defect symmetrically to the MZI, the resonance still takes place at the eigenfrequency of the defect \(E_F\). In this spatially symmetric case, the coupling to the upper arm is somehow reduced, and there is only one resonance of the Fano defect with the lower arm. But, the situation is drastically changed when the Fano defect is attached asymmetrically (see Fig. 2). In this situation, there are two Fano resonances. Each resonance can be associated with the interaction of the side-coupled defect with one of MZI arms. When the defect is placed symmetrically, the waves propagating clockwise and counterclockwise acquire the same phase accumulation, and, eventually, canceling each other leading to zero effective coupling with the upper arm. That’s why the resonance takes place at the eigenfrequency of the defect, in similarity to the straight waveguide. For asymmetrically placed Fano defect, clockwise and counterclockwise waves acquire different phase accumulation resulting in different resonant conditions. The side-coupled defect can be considered as an additional degree of freedom for scattered waves to propagate, making the MZI to consist of three arms, instead of two. It turns out that the role of this effective arm is significant for the final outcome due to sharp variation of the phase.
In conclusion, we have discussed the properties of a novel Mach–Zehnder–Fano interferometer created by inserting a cavity into the conventional MZI. We have demonstrated that the excitation of the cavity mode changes dramatically the transmission characteristics of the structure such that the coupling between the arms is effectively suppressed due to the Fano-induced destructive interference. By changing the position of the cavity, the transmission coefficient can be altered dramatically. We have implemented this novel Mach–Zehnder–Fano geometry in two-dimensional photonic crystals, and observed a striking similarity between the transmission characteristics of the effective discrete model and direct numerical simulations.

This work was supported by Discovery and Centre of Excellence projects of the Australian Research Council (ID: DP0771218).