Multiport interferometer from a multimode waveguide

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The introduction of bends into multimode waveguides is known to have undesirable effects on the transmitted information due to mode mixing. Here, we leverage the mode mixing to construct multimode interferometers with a predefined transfer matrix. Using the inverse-design method, we have investigated the capabilities of such type of interferometers to perform useful tasks.

Keywords: *Multimode waveguides, waveguide bends, photonic information processing*

INTRODUCTION

Multiport interferometers find wide applications in photonic technologies. The interferometers should be capable to transforming the orthogonal field modes according to a predefined matrix U, such that the output vector of field amplitudes $\boldsymbol{b}$ is related to the input vector $\boldsymbol{a}$ by multiplication on the matrix**:** $\boldsymbol{b} = U\boldsymbol{a}$. In particular, performing matrix-vector and matrix-matrix multiplication, the subroutine intensively used in neural networks, using proper multimode photonic elements, can be more energy efficient than the traditional electronic approaches [1]. Multiport interferometers also play an essential role in quantum simulators, which use the unique properties of photon interference to perform quantum operations [2].

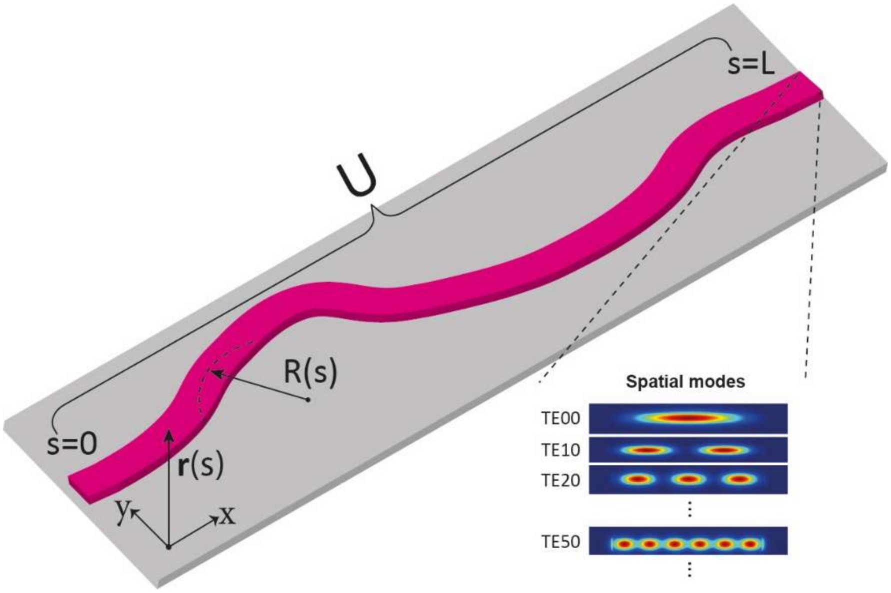

Fig. 1. Illustration of the proposed multiport interferometer: the multimode waveguide implementing a mixing transformation over the spatial modes propagating through it.

Many applications of multiport interferometers require the transfer matrix U to be programmable to perform a specific transformation. For this purpose, several design methods exist that enable one to construct universal schemes that can be reprogrammed to any given transfer matrix by setting proper values of the constituent phase shifters (see, for example, [3]). However, in some applications, one needs only to multiply by a static matrix throughout the whole lifespan of the device. Therefore, considering the need for scaling the multiport devices, using the programmable designs for static interferometers can be overly complex. It is of interest to develop new approaches for designing such static interferometers.

In integrated photonics, the spatial degree of freedom is often exploited, either solely or combined with another degree of freedom. In particular, the multiport interferometers constructed from single-mode waveguide elements are widely used in classical and quantum photonics due to the simplicity of circuit design. In contrast, we investigate the capability of the multimode waveguide to perform linear transformations over the propagating spatial modes.

Using multimode waveguides in integrated photonics can be beneficial, as the devices can be more compact than their single-mode counterparts. In addition, the multimode waveguides can be more easily coupled with photon sources and detectors, especially with quantum emitters.

The proposed multiport interferometer is illustrated in Figure 1. The main element is a planar multiport waveguide with a rectangular cross-section and variable guiding direction, as defined by the dependence of the vector $\boldsymbol{r}(s) = (x(s), y(s))$ pointing to the waveguide centre, where s is the coordinate along the waveguide path with L being the length of the path ($0 \leq s \leq L$). This section is where the controlled inter-mode mixing is implemented to obtain the target transfer matrix between modes of interest. The encoding of the input and output amplitudes $\boldsymbol{a}$ and $\boldsymbol{b}$ is in a set of orthogonal spatial modes of straight waveguides connected to the input and output of the curved MMW. The waveguide path $\boldsymbol{r}(s)$ is completely defined by the local curvature dependence $\kappa(s) = 1/R(s)$, which can take a positive or a negative value, depending on the side where the curvature centre is located with respect to the waveguide section center $\boldsymbol{r}(s)$ and $\kappa(s) = 0$ for a straight section. The inverse-design methods, which have attracted appreciable interest in the recent years, can tackle such tasks [4].

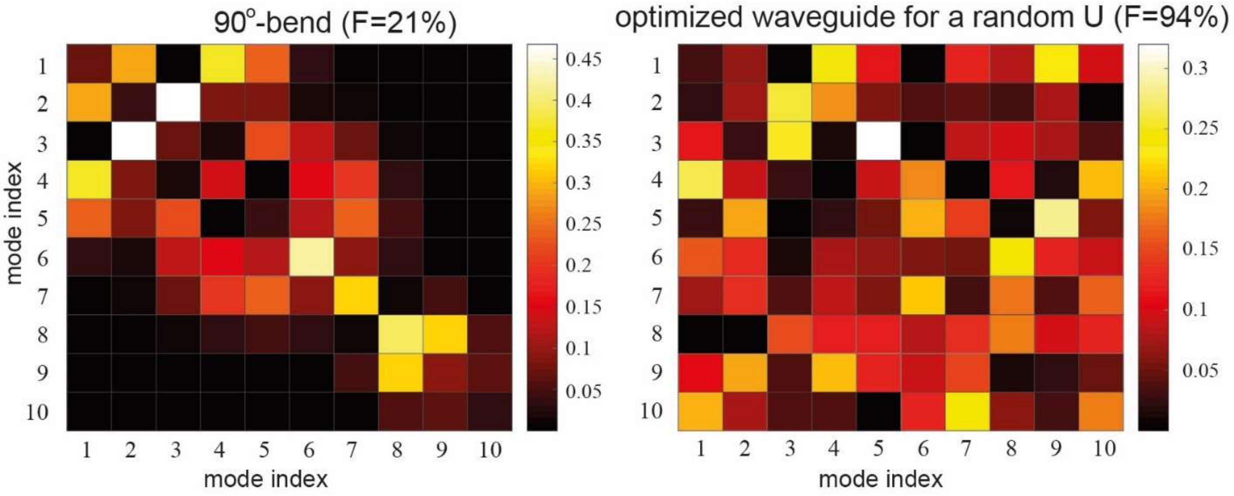

Fig. 2. Histogram of power transfer matrices, corresponding to the 90°-bend of silicon waveguide of $\boldsymbol{R} = \mathbf{10}$ mkm radius (left) and a waveguide with optimized path to implement a randomly generated transfer matrix (right). The following waveguide parameters were used in simulation: (height) $\boldsymbol{h} = \mathbf{0.2}$ mkm, (width) $\boldsymbol{w} = 3$ mkm, (wavelength) $\boldsymbol{\lambda} = \mathbf{1.55}$ mkm.

RESULTS

To find the optimal waveguide path $\boldsymbol{r}(s)$ implementing a desired unitary matrix as close as possible, numerical optimization has been exploited, which were searching for a global maximum of the fidelity measure: $F = |Tr(UU_0^+)|^2/M^2$, where U_0 and U are the target and the actual transfer matrices, M is the matrix size (number of supporting modes). Direct calculation of the transfer matrices requires calculation of field dynamics through the waveguide, which in turn necessitates numerical solution of equations on a 3D grid. To alleviate the burden of computing time, we reduced the full 3D equations for field to equations of propagation of the spatial modes that depends on one spatial variable s and some functional parameter that can be pre-calculated numerically once the waveguide cross-section and materials are given.

Fig. 2 illustrates one example of the approach. Here, the target transformation was to perform mode mixing with a transfer matrix U_0 generated at random from a uniform distribution. The choice of random matrices is motivated by the architecture of programmable interferometers, which we proposed earlier [5]. The figure shows two cases. The left histogram corresponds to an unoptimized multiport bent, supporting $M = 10$ TE modes. Even though the mode mixing is clearly present, it does not provide full mode mixing, thus, the low fidelity $F = 21$ %. The histogram on the right is obtained for the waveguide of the same cross-section, however, its path $\boldsymbol{r}(s)$ has been optimized with respect to the fidelity measure: $F \sim |Tr(UU_0^+)|^2$, where U is the actual transfer matrix, obtained in the course of optimization. In this example, the archived fidelity $F = 94$ %. We have investigated the proposed approach considering several useful transfer matrices, very often required in photonic information processing, including the discrete Fourier transform and Hadamard matrices.

DISCUSSION

In our work we have investigated a new approach to create static multiport interferometers operating on spatial modes of multimode waveguides. The interferometers can perform some useful multiport transformations and they can be utilized either as stand-alone elements performing specific transfer matrices, or as parts of programmable interferometers, such as those proposed in [5].

Acknowledgements: M.S., S.F., I.D. and S.S. acknowledge support by Rosatom in the framework of the Roadmap for Quantum computing (Contract No. 868-1.3-15/15-2021 dated October 5, 2021 and Contract No. P2154 dated November 24, 2021). Authors acknowledge partial support by the Interdisciplinary Scientific and Educational School of Moscow University ”Photonic and Quantum Technologies. Digital Medicine”. M.S. and S.F. are grateful to the Foundation for the Advancement of Theoretical Physics and Mathematics (BASIS) (Projects No. 20-1-3-31-1 and 22-2-1-89-1). S.K. is supported by the Ministry of Science and Higher Education of the Russian Federation on the basis of the FSAEIHE SUSU (NRU) (Agreement No. 075-15-2022-1116).

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