Design of High Order Mode-Multiplexers using Multiplane Light Conversion

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Abstract *We design a spatial mode multiplexer using multi-plane light conversion which can address all 45 modes of a 50-μm graded index multimode fiber at 1550 nm with 14 phase planes. The mode-dependent loss is below 2-dB across 100 nm.*

Introduction

Multi-plane light converters[1,2] (MPLC) and photonic lantern[3] mode-multiplexers can demultiplex over 10 modes with low losses. Photonic lanterns are adiabatic mode-multiplexing devices that convert the fundamental mode on many single-mode fibers into the different modes of a multimode fiber (MMF) core through a continuous changing refractive-index profile. Desirable properties of adiabatic transitions include reduced fabrication tolerances and ultra-wideband operation. A MPLC converts between two sets of orthogonal free-space beams through many phase planes separated by free-space propagation. Typically, MPLCs require ”inverse” design[4], or computed generated solutions to determine the phase profiles, and the masks are often complex and not intuitive. Theory indicates that for extreme cases, MPLC requires only two planes per mode[2] but does not specify a minimum number of planes. Recently a 10-mode device was fabricated with 14-planes[5]. Using these scaling rules, a 45 mode device would require 60-90 phase planes which would have high loss from reflections. Here, we show how to build a MPLC the supports 45 modes in 14 planes which has adiabatic properties similar to photonic lanterns.

Insights into Multi-Plane Light Conversion

Optical devices can be described by a continuous refractive index profile in three dimensions or as having refractive index clumped at discrete positions such as a lens system [Fig. 1]. Entering the device with orthogonal spatial profiles (or positions) will produce unique outputs. The N fields at the input and the output of the device and the refractive index are denoted as $f_i(z,x,y)$, $b_i(z,x,y)$, and $n(z,x,y)$. For continuous systems, n is specified for all z. For multi-plane systems n is only defined at discrete locations spaced by Δz and is represented as a phase shift $\Phi_k(x,y)$ at plane k. The discrete version of

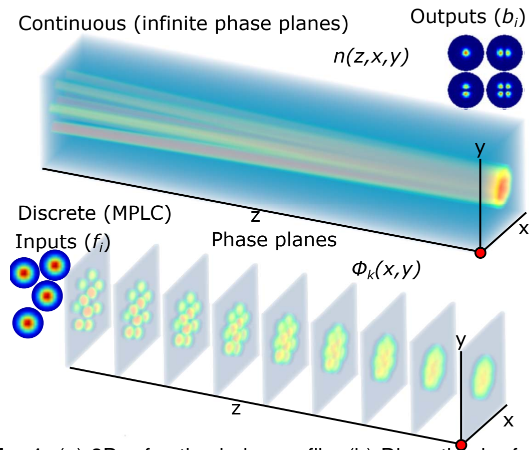

Fig. 1: (a) 3D refractive index profile. (b) Discretized refractive index profile represented as multiple phase planes.

the device behaves exactly like the Fourier transform beam propagation method. With enough phase planes, a MPLC could approximate a waveguide device such as a photonic lantern.

Only a subset of continuous devices can be approximated with a small number of planes. For instance, step-index devices which have large refractive-index steps would translate into phase masks with large phase discontinuities which scatters light at large angles. Highly divergent beams may not be captured by successive phase planes, and have stronger wavelength dependence. Alternatively, discrete approximations of waveguide devices with graded index profiles can have much larger spacing because they will not introduce phase discontinuities and will have less wavelength dependence (i.e., adiabatic). When masks are spaced farther apart, they must also refocus the beams to minimize divergence. Therefore, most MPLCs we simulate tend to be smooth and have lens-like features which allows for larger separation of phase planes. Finally, the number of planes should scale with the product of the spatial modes, and the operation bandwidth (i.e., spectral modes). This is just another form of the adiabaticity requirement.

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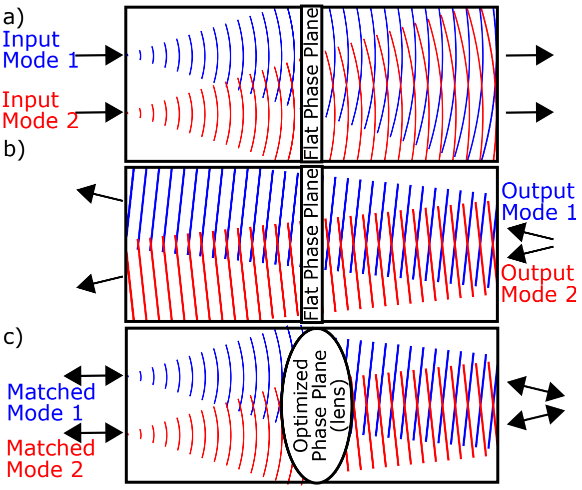

Fig. 2: Phase fronts in the wavefront matching method for a single phase plane. a) Input modes propagated forward and b) Output modes propagated backward. c) Input modes match the output modes propagating backwards.

Wavefront Matching Optimization Algorithm

We modified the wavefront matching method[6] to optimize the phase planes. Wavefront matching propagates the input fields forward through the system [Fig. 2a)] and the output fields backwards through the system [Fig. 2b)]. The only way for an input to excite an output is if the phase fronts of the N forward propagating inputs, f_i, and backward propagating outputs, b_i, match at every spatial coordinate. When the fields do not match, the phase error at each spatial coordinate can be computed and subtracted from that phase plane. In a multi-plane system, the algorithm moves all f_i and b_i forward together to the next plane or backwards together to the previous plane and iterates until the error is minimized. For the scenario depicted in Figure 2c), a simple lens with quadratic phase matches the forward propagating input and backward propagating outputs at all spatial coordinates. In the simulations, f_i and b_i are propagated between planes using the angular spectrum method which is accurate for large angles and can be modified to support tilted planes[7].

The phase correction, $\Delta\Phi_k(x, y)$, applied to each plane can be computed through the field overlap matrix at the k-th plane:

$$o_{kij}(x, y) = f_i(k\Delta z, x, y)\overline{b_j(k\Delta z, x, y)} \exp(\jmath\Phi_k(x, y))$$

The overlap integral matrix, $\mathbf{O_k}$, with entries $O_{kij}(z) = \int\int o_{kij}(x, y)dxdy$, quantify how well each input mode couples to each output mode. Our goal is to maximize $\operatorname{Tr}\mathbf{O_k}$ for mode selective devices and to minimize the mode-dependent loss (MDL) and insertion loss (IL) for non-mode selective devices. MDL is defined as the square of the ratio of maximum to minimum singular value of $\mathbf{O_k}$ and the IL is the inverse of the mean of the squared singular values. Since phase masks, and free space propagation are unitary operations (i.e., no power absorbed), the magnitude of $O_{kij}(z)$ must be invariant with z. However, at each z, the spatial profile of $o_{kij}(x, y)$ can be very different. This implies that a local phase optimization will minimize the global error.

The optimization technique finds the phase profile which maximizes $\operatorname{Tr}\mathbf{O_k}$ by taking the weighted averaged of all of the field overlaps

$$\Delta\Phi_k(x, y) = -\arg\Big(\sum_i o_{kii}(x, y)\exp(-\jmath\phi_i)\Big)$$

where ϕ_i is the average phase of o_{kii}. Note, when $\operatorname{Tr}\mathbf{O_k} = \mathbf{N}$ the MDL and IL are 0 dB. Once $\Phi_k(x, y)$ is updated, f_i and b_i are propagated together either forwards or backwards through the system to the next plane.

This gradient descent algorithm asymptotically reduces the error. Unfortunately, it can converge into local minima. Constraints can be applied to favor adiabatic solutions which are broadband and fabrication tolerant. These include limiting the angle space, limiting the size of the masks, preventing updates in areas with low power, forcing adjacent masks to look the same, zeroing masks, and averaging the $\Delta\Phi_k(x, y)$ over multiple wavelengths.

Design of a 45-Mode Spatial Multiplexer

Figure 3 shows the design of a 45-mode spatial multiplexer that converts a linear array of Gaussian beams with w_0 of 30 μm at 127-μm pitch into the first 9 mode groups of a graded index MMF that are collimated with a 2-mm focal length lens. The device has 5-μm pixel pitch, 512$\times$1280-pixel mask size, and 24-mm Δz.

The algorithm converges to the least number of planes when the MMF modes are represented as the Hermite-Gaussian (HG) basis rather than the linearly-polarized (LP) basis, or orbital angular momentum (OAM) basis and when the input beams are rearranged into a triangle shape [Fig. 3a)] with the indicated target mode placement. We believe the symmetries of the modes and the arrangement of spots in the triangle enable a device with a much reduced number of planes. Starting from any position on the triangle, moving up-left(down-left) a diagonal increases the zero transitions by one along that diagonal direction and moving up-right(down-right) a diagonal decreases the zero transitions by one along that diagonal direction. The algorithm runs on a GPU, and converges in about 10000 iterations.

The device has three unique regimes: **1** remapping the linear array into a triangle, **2** converting between the triangle and the HG modes, and **3** beam resizing to match the output mode field diameter. From **1** to **2** requires 7 masks in order to maintain broadband operation. The transition between **1** to **2** could be accomplished

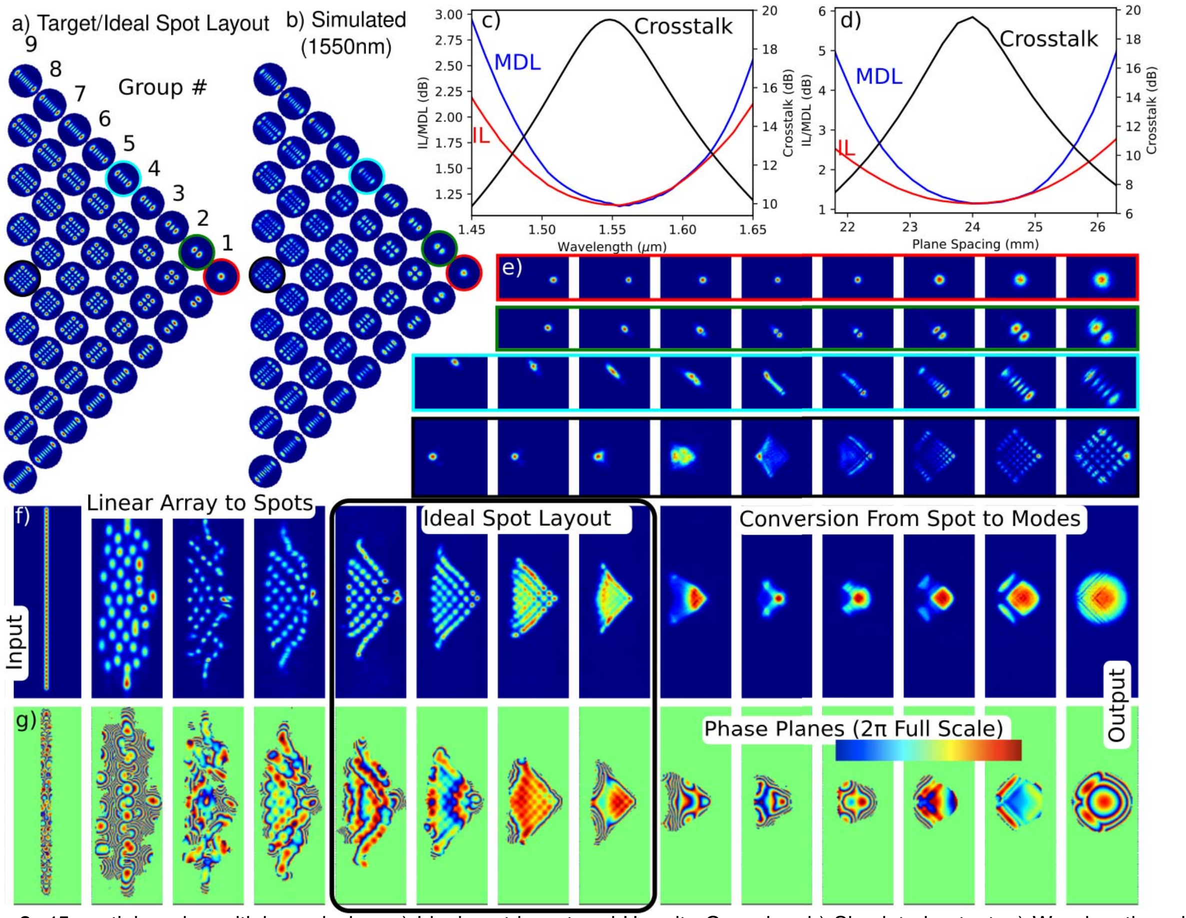

Fig. 3: 45 spatial mode multiplexer design. a) Ideal spot layout and Hermite-Gaussian. b) Simulated output. c) Wavelength and d) plane spacing sensitivity. e) Selected modes intensity at different planes. f) Sum of intensity of all modes. g) Phase planes.

in fewer masks, but the outer beams would suffer larger diffractive losses further from the center wavelength. The transition from **2** to **3** used 7 masks. Increasing the plane count only improves throughput and enlarges bandwidth.

The device is adiabatic, which is visualized by the mode profiles (shown from **2** to **3**) smoothly morphing into the desired modes and from the smooth looking masks. Most masks have little or no phase jumps, and all jumps are 2π which could be unwrapped into a continuous phase profile. A few of the masks have large quadratic phases which primarily corrects for curvature and refocuses the beams. Additional optimizations to the algorithm could attempt to redistribute the curvature.

Figure 3b) shows the simulated output of the device at 1550 nm which match well with the target modes [Fig 3a)]. Figure 3c) shows the MDL/IL and crosstalk (defined as the ratio of the power in the target modes to the power collected in the other modes) across wavelength. The MDL is below 2 dB for over 100-nm bandwidth, and the best crosstalk is 19.5 dB. Figure 3d) shows MDL/IL and crosstalk vs. mask spacing. The MDL is below 2 dB for a 10% error in the Δz which indicates a fabrication tolerant design.

In conclusion, we described how to design high order mode multiplexers using MPLC with a significantly reduced number of masks. The algorithm produced adiabatic solutions with large bandwidths. The triangle spot arrangement, and choice of HG modal basis enabled the device with the least number of planes.

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