# Mode Order Converter Using Tapered Multi-mode Interference Couplers

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**Abstract:** Tapered MMI devices are proposed. It is demonstrated that the proposed single-stage MMI device's output power efficiency can be 55% higher than a conventional adiabatic taper by partially capturing the 2nd order mode power.

**OCIS codes:** (130.3120) Integrated optics devices; (130.2790) Guided waves

## 1. Introduction

Accommodating various sizes, shapes, and modes of guided light is essential for flexibility in photonic integrated circuit (PIC) design. Specifically, spot-size and waveguide mode order conversion can allow PICs to utilize a wide range of laser sources as well as many waveguide geometries. Tapered structures are commonly used to perform the necessary profile shaping.

In adiabatic tapers the waveguide width changes so slowly that mode conversion is negligible [1, 2]. Therefore, if the taper output is a singlemode (SM) waveguide, all the input power in the high order modes is radiated away, while the power in the input fundamental is perfectly transmitted into the output waveguide. In short tapers, mode conversion has a vital role. Despite the advantage of shorter lengths, such tapers suffer from severe tolerance control of the structure's geometry and refractive indices. One can define $A_{m0}$ as the transmission of the fundamental mode in the output guide when exciting the input guide with its normalized $m^{th}$ order mode [2]. For the SM output waveguide, short or abrupt tapers can result in non-zero $A_{m0}$, for $n>1$. However, the mismatch between the fields of the fundamental modes in the input and output significantly lowers $A_{00}$.

Our goal is to use tapered 1×1 MMIs with a multimode (MM) input and a SM output in order to extract and convert power from the high order modes in the input to the SM output without jeopardizing the conversion efficiency of the input fundamental mode. Instead of directly converting MM to SM, most MMI designs act as N×N switches, splitters, or multiplexers [3, 4, 5]. To our knowledge, utilizing an MMI to interface one MM input with one SM output has not been reported.

## 2. Tapered MMI design

For a straight MMI device, the single image of the input field distribution repeats itself every $3L_\pi$, where $L_\pi=4n_cW_e^2/3\lambda_0$, $n_c$ is the refractive index of the MM waveguide core, $W_e$ is the effective MMI width, which includes the geometric width of MMI and mode penetration into the cladding layers, and $\lambda_0$ is the wavelength in vacuum. When the MMI input is restricted to symmetric excitation, the required device length becomes four times shorter ($3L_\pi/4$). Since MMI length is proportional to the square of the MMI width, tapered MMIs have been utilized to reduce device length by a factor of 3 to 4 [3]. Recently, compact 2×2 parabolically tapered MMI couplers were theoretically and experimentally investigated [3, 4, 6]. When an MMI width is tapered down with respect to its width at the input, we notice that the output image is also reduced in width. The overall transmission can approach 100% provided that (1) the taper structure is adiabatic, (2) the excited high order modes at the input of the MM waveguide are supported by the width of the MM waveguide at the output. The question to be answered is what happens to the high order input modes when the output waveguide is SM [see Figure 1 (a)]. Although all input field profiles decompose into the modal field distributions of the MM waveguide, the field excitation components of the high order modes are stronger in the case of high order mode inputs compared to the fundamental mode input [5].

Since high order modes in the MM waveguide are more likely to be radiated out of the waveguide at the narrowed region, we expect lower transmission for these modes. Additionally, since the number of modes supported by the MM waveguide at the output can be fewer than the input, the image resolution at the output can be too coarse to resolve the field variation of the input high order modes. Thus, a low resolution image of a high order mode input can excite the SM output waveguide as it happens in abrupt tapers.

In order to investigate the performance of tapered MMIs with an MM input and an SM output, we first discuss the design methodology. For any MMI structure, the input field profile at $z=0$ can be written as a linear combination of the MM waveguide propagating modes,

$$\Phi(x,y,z=0)=\sum_{m=0}^{M} c_m \phi_m(x,y), \tag{1}$$

where, $c_m$ is the excitation coefficient calculated as the overlap integral of the input field ($\Phi$) and the $m^{th}$ mode ($\phi_m$), and $M$ is the total number of supported guide modes. The field profile at $z=L$ can be written as

$$\Phi(x,y,z=L)=\sum_{m=0}^{M} c_m \phi_m(x,y) e^{j\varphi_m L}. \tag{2}$$

The accumulated phase of the $m^{th}$ mode is given as

$$\varphi_m(z)=\int_0^z n_{eff,m}(z')k_0 dz', \tag{3}$$

where, $k_0=2\pi/\lambda_0$ and $n_{eff,m}$ is the effective index of the $m^{th}$ mode, which is a function of the MMI width at $z$. In order to have a single image at $z=L$ in the case of a symmetric excitation we must have

$$\Delta\varphi_2(L)=\varphi_0(L)-\varphi_2(L)=2\pi. \tag{4}$$

Note that no odd modes are excited in the case of symmetric excitation, which is the case in the tapered 1×1 MMI. We calculated $n_{eff,m}$ at $\lambda_0$=1.55$\mu m$ for the first two even modes in silicon-on-insulator based devices [Fig. 2(a)].

We assume an MM $t_1=2\mu m$ wide input silicon waveguide and an SM $t_2=0.5\mu m$ wide output silicon waveguide. The thickness of the silicon layer is $0.25\mu m$. The input polarization is assumed to be TE. Note that polarization-insensitive waveguiding structures [7] can be used for polarization-independent mode conversion. Since the input fundamental mode should be tapered down to $r=t_2/t_1$ of its original width, we should have $w_2/w_1=r=1/4$. Therefore, knowing the input and output waveguide widths and the MMI input width, we can find the MMI length, $L$, using Equation (4) for any taper profile. We consider two tapering profiles, linear and parabolic tapering, described as $w(z)=w_2+(w_1-w_2)(L-z)^2/L^2$. Figure 1(c) shows the variations of MMI length ($L$) versus $w_1$ for $w_2/w_1=1/4$ for both linear and parabolic tapering. Note that once the input and output widths are set, the MMI length, as well as the tapering angle, are derived from equation (4). Therefore, tapering angle is not an independent design parameter.

## 3. Simulations and discussions

Beam propagation simulations (BPM) have been commonly used to characterize MMI-based devices [1, 4, 6]. We model our 1×1 MMI coupler structures with linear and parabolic tapering. Figures 2(a) and (b) show how a fundamental mode and a second order mode, respectively, propagate in the tapered MMI structure and excite the SM output waveguide. As depicted in Figure 2(a), this process is very efficient in the case of the fundamental mode, where the tapered MMI structure acts similar to a conventional adiabatic MM-to-SM waveguide taper. In the case of the second order mode input [Figure 2(b)] some of the strong high order modes excited inside the MMIs are not supported at the narrowed output width of the tapered MMI. However, the SM output waveguide still receives a considerable excitation. An important observation is that the 1-fold image of the input forms at slightly different distances in Figures 2(a) and (b). In Figure 2(b), the 1-fold image formation plane is 0.1µm closer to the input. This defocus effect is due to the relatively smaller $n_{eff}$ values of the high order modes.

Figure 2(e) demonstrates the variation of transmission coefficients ($A_{m0}$) versus the input MMI width ($w_1$) for the fundamental, second order, and the fourth order mode inputs in both the linear and parabolic taper cases. In the case of the fundamental mode transmission ($A_{00}$), the linearly tapered structure efficiency remains above 98.5% in all cases. The parabolically tapered structure is less efficient, which can (especially in longer devices) be attributed to the increased radiation of high order modes out of the narrowed output of the MMI. In the case of $A_{20}$, the conversion efficiency depends on the output width of the MMI structure which is more prominent at smaller widths. $A_{20}$ conversion also depends on the defocus effect, which is more prominent in longer (or equivalently wider) devices. Thus, $A_{20}$ is slightly lower at both large and small widths in both linearly and parabolically tapered MMIs. The defocus effect is less effective in parabolically tapered MMIs due to their shorter lengths and $A_{40}$ is considerably larger for the parabolic taper compared to the linear taper. Thus, if the input excitation contains both the 0th and the 2nd order modes of the same power, the field amplitude in the SM output can be 25% higher compared to an adiabatic taper of the same input and output waveguide widths as depicted in Figure 2(c) and (d). This results in over 55% increase in the output power. To achieve such efficiency, the 0th and 2nd order input excitation in the SM output waveguide should be in phase. This phase matching condition is required for all mode converter/combiners [8] [5], where all modes have the same frequency, such as exciting an MM planar waveguide using an MM fiber that was originally excited using a single wavelength end-fire. However, if the modes are in slightly different wavelengths, such as the transverse modes of a diode laser [9], the SM output waveguide contains fundamental modes of different wavelengths, and the relative phase is not important. In summary, when directly excited by diode lasers, the presented tapered MMI coupler can directly convert the fundamental and second order transverse modes of different wavelengths into the fundamental mode signals of a SM waveguide. Compared to the previously presented MMI based mode converters [5], since it consists of a single stage MMI the results can be implemented in optical fibers for MM fiber to SM fiber coupling. All fiber MMI-based components, such as band-pass filters and refractometer sensors have been theoretically and experimentally demonstrated [10].

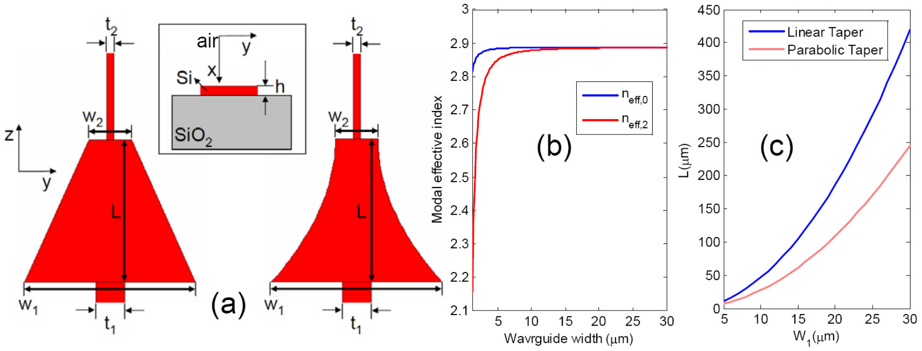

Figure 1. (a) Schematics of linear and parabolic tapering. Inset shows a cross-section view of the waveguide structure. (b) Effective indices of the zeroth and the second order TE polarization modes versus waveguide width for a waveguide thickness of $0.25\mu m$, $n_{Si}=3.47$, $n_{SiO2}=1.45$. (c) Variations of MMI length with the output/input width ratio being $w_2/w_1=1/4$ for linear and parabolic tapering types.

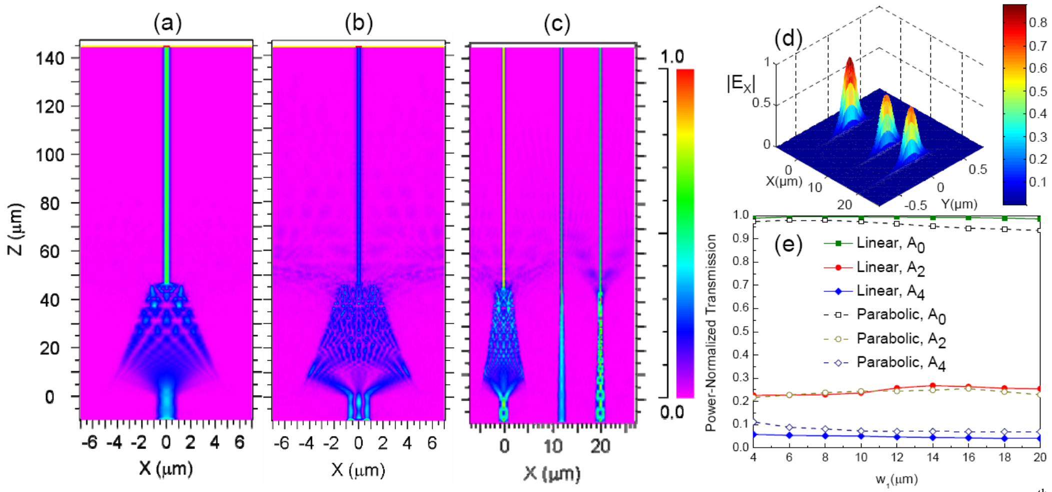

Figure 2. BPM simulations of a linearly tapered 1×1 MMI coupler, $w_1=10\mu m$, $w_2=2.5\mu m$, $t_1=2\mu m$, $t_2=0.5\mu m$ and $L=46.4\mu m$ for (a) 0th order mode and (b) 2nd order mode input excitations. The input power is the same in (a) and (b). (c) and (d) show the XZ and XY field profiles, respectively for the structure shown in (a) and (b) and a conventional taper of the same length and input/output width exited by 0th and 2nd order modes of the same power, and a conventional taper excited only by the 0th order mode. (e) Output SM waveguide field amplitude normalized to the output field amplitude of a conventional MM (width=$2\mu m$) to SM (width=$0.5\mu m$) adiabatic taper excited by the fundamental mode of the same input power.

## 4. References

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