Design and fabrication of 1xN and NxN planar waveguide couplers for multimode fiber-based local area networks

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***Abstract**:- We report on the design and fabrication of compact and potentially low-cost multimode fiber matched 1 x N and N x N couplers for LAN's. The design utilizes the self-imaging effect and tapering of the Multi-Mode Interference (MMI) section. An extended mode propagation analysis and 3-D beam propagation method (BPM) were used to analyze and design these structures. The simulations show that the couplers exhibit low excess losses, low power imbalance, and relaxed fabrication tolerances at very short device length. The devices were fabricated in polymer waveguide technology using spin coating, photolithography, and reactive ion etching. Preliminary experimental results show promising characteristics.*

Introduction

Multimode fiber technology and increasingly multimode planar waveguide devices are largely employed in short-distance communications applications such as local area networks and interconnects. Despite the advantages of the multimode technologies there is a notable lack of affordable planar multimode components that are capable to perform advanced network functionalities.

In this work novel designs of planar multimode *1 x N* power splitters and *N x N* star couplers, which utilize the self-imaging effect and a tapered MMI section, see Fig. 1, are proposed and demonstrated. With the aid of self-imaging the input power can be distributed equally and focused on the output ports resulting in low excess losses and small power imbalance. By applying a tapered geometry for the MMI section, the coupler length can be substantially shortened while the imaging properties can be maintained. We extended the modal propagation analysis (MPA) to handle cases of tapered couplers that are multimodal both in vertical and horizontal directions [1,2]. To check the benefits of these designs, in term of the excess losses and power imbalance, and the validity of the MPA, a 3-D Beam Propagation Method (BPM) [3] has been used. The designed devices have been fabricated in polymer waveguide technology, which we have specially developed for large cross section multimode waveguides.

In section II the devices structures will be analyzed and the design rules will be summarized. Designs of the couplers and results of BPM simulations will be given in section III. In section IV the fabrication process and experimental results will be presented and discussed. Finally, conclusions will be given tin

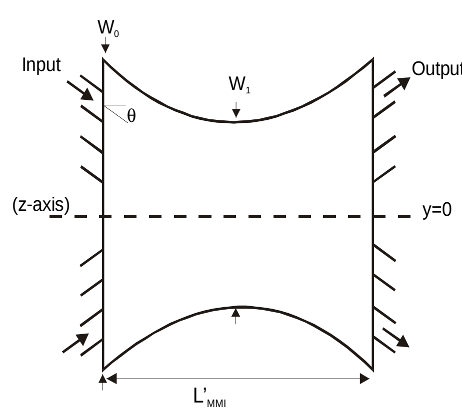

Figure 1: A schematic layout of N X N tapered coupler.

section V.

II Analysis and Design rules

The self-imaging effect has previously been studied in waveguides that are highly multimodal in both the lateral (x) and transverse (y) directions [1]. In this case the propagation constant β_{mn} of a $(m, n)^{th}$ order mode is given approximately by:

$$\beta_{mn}^2 \cong (n_c k_0)^2 - k_x^2 - k_y^2 \quad (1)$$

where n_c is the core refractive index, $k = n_c k_0$ (= $2\pi/\lambda$) is the wavevector and k_x and k_y are its respective x- and y-axis projections. Using some approximations [4], the difference in propagation constants of the fundamental and both lateral and transverse first order modes can be expressed as

$$\Delta\beta_{10} = \beta_{00} - \beta_{10} = \frac{3\lambda\pi}{4n_c w^2}, \quad \Delta\beta_{01} = \beta_{00} - \beta_{01} = \frac{3\lambda\pi}{4n_c h^2} \quad (2)$$

with h and w being the coupler's height and width, respectively. For an aspect ratio p = w/h, we have $\Delta\beta_{01} = p^2\Delta\beta_{10}$. The relative difference in phase $\Delta\varphi_{mn}$ between the $(m, n)^{th}$ order and the fundamental mode after propagation over a distance $z = z_0$ can for an integer p be written as:

$$\Delta\varphi_{mn}(z_0) = \int_0^{z_0} \Delta\beta_{mn} \cdot dz = \frac{\Delta\beta_{10}}{3}\left[m(m+2) + p^2 n(n+2)\right] \cdot z_0 \quad (3)$$

Now when p^2 is even, the second term in the square brackets in (3) is even, and the symmetry of the square bracketed term is entirely determined by m, i.e., it is even when m is even and odd when m is odd. This condition makes relation (3) entirely analogous to the case of self-imaging in single-transverse-mode waveguides [5]. Consequently, the coupler length z at which N-fold images occur, for instance in an N x N coupler, can be given by

$$z = L_{MMI} = \frac{M}{N} \cdot \frac{3\pi}{\Delta\beta_{10}} = \frac{M}{N}\frac{4n_c w^2}{\lambda} \quad (4)$$

where M (M=1 for the first image plane) and N are integers having no common devisor with N being the number of the access ports.

When the MMI region is tapered along the propagation direction, $\Delta\beta_{10}(z)$ replaces $\Delta\beta_{10}$ in the integration (3), and using the parabolic taper design given in [2], the self-imaging length for an $N \times N$ coupler can be scaled down to

$$L'_{MMI} = \frac{M}{N} \cdot \frac{3\pi}{\Delta\beta'_{10}} = \frac{M}{N} \cdot \frac{4n_c w^2}{\lambda} \cdot \frac{1}{\chi} \quad (5)$$

where χ is a geometry-dependent factor based on the start and minimum taper width of the coupler (see [2] for details).

III Design and simulations

using relation (5) we have designed a number of 1 x 2, 2 x 2 and 4 x 4 tapered multimode couplers. The dimensions of the couplers' access waveguides were designed to be 40 x 40 μm^2 and the refractive index contrast was 0.027 at a design wavelength of 0.85 μm. The refractive index contrast and channel waveguide dimensions are chosen in practice to satisfy the simultaneous requirements of minimizing coupling losses with standard multimode fiber while utilizing the refractive index values of cheap, widely-available polymeric materials. The 1 x 2 and the 4 x 4 couplers have been tapered down to different minimum widths, as shown in Table I, to study the influence of tapering on the device performance. From Table I it can be seen that the device length of a tapered coupler can be significantly reduced in comparison to the length of straight coupler, which can be calculated using relation (4).

MMI coupler type	Start/ min. taper width [μm]	MMI length [μm]	Excess loss [dB]	Imbalance [dB]
1×2	100/100	8883	0.03	0.015
	100/71	5684	0.04	0.02
	100/43	2842	0.15	0.05
2×2	100/43	9810	< 0.01	0.35
4x4	175/153	45445	0.12	0.50
	175/108	28423	0.60	0.28

Table 1. Performance characteristics of various parabolically-tapered multimode MMI couplers, simulated using 3-D BPM software [3].

We have used 3-D BPM software to simulate and optimize the design of parabolically-tapered multimode MMI couplers. Results from 3-D BPM simulations, presented in Table I, show that very low excess losses and power imbalance have been obtained for very short devices. Note that there is no a significant increase in the excess losses as the devices length become shorter. This indicates that tapering induced radiation losses are insignificant.

In the above results we have used a Gaussian beam as an input field excitation. To determine the sensitivity of the couplers to varying multimode fiber excitation conditions, different input fields have also been used. For a field with power uniformly distributed over the waveguide cross-section, the resulting excess loss and imbalance values are 0.25 and 0.19 dB, respectively, for the 1×2 coupler. Relevant for ease of fabrication and low-cost packaging, the designed couplers exhibit relaxed tolerances. With a Gaussian input field, a 1×2 coupler with a length deviation of $\Delta L'_{MMI} = \pm 50\ \mu$m exhibits excess losses and imbalance of 0.20 and 0.10 dB, respectively. The couplers are also wavelength insensitive with excess losses of < 0.30 dB for $\Delta\lambda = \pm 40$ nm around the center wavelength of 850 nm.

IV Fabrication and characterizations

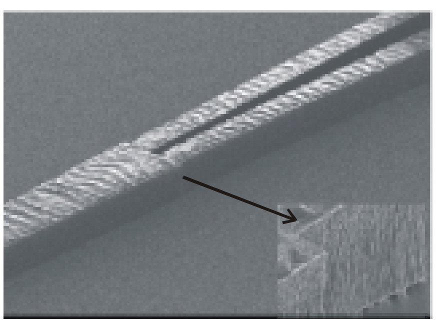

Figure 2: SEM electron micrograph of a 1 x 2 tapered coupler. A close up showing the side-wall roughness is shown in the inset.

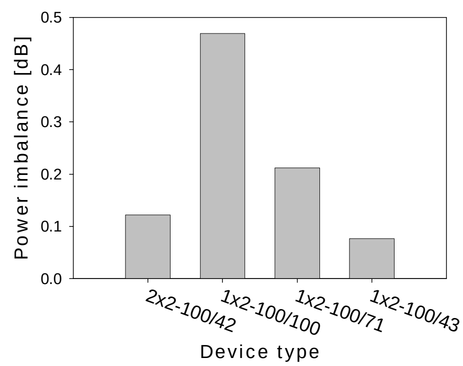

Figure 3: Measured values of the imbalance of different couplers. As a parameter the device type and the start and minimum widths of the tapers are shown.

The couplers were fabricated in polymer waveguide technology [6]. Fig. 2 shows a SEM picture of a part of one of the realized 1 x 2 power splitters. We have done preliminary experiments to characterize the performance of the realized couplers for power imbalance and the excess losses. In Fig. 3 a histogram that shows the measured power imbalances of various 1 x 2 power splitters with different lengths and a 2 x 2 coupler is presented. The obtained power imbalances are low and are only slightly higher than the simulations results. Note that the imbalance depends on the excitation conditions; the values presented here are taken for optimum fiber-to-chip coupling. Excess losses of ~ 1.5 dB were measured for all couplers. No notable variations in the excess losses between different couplers were observed, indicating that taper induced radiation losses are indeed insignificant as the simulations have shown.

Fig. 4 shows the normalized output power measured for the 4 output channels of two 4 x 4 star couplers; one with coupler length of 45.5 mm and the other has a length of 28.4 mm. There is a power imbalance of ~2 dB as measured between asymmetrical output channels, i.e. between channel #1 and #2. The relatively large power imbalance is probably due to coupling between the access waveguides which are closely spaced at the start and the end of the couplers. It can be noticed that between the symmetrical output channels the power imbalance is extremely low. Excess losses of ~ 1.5 dB measured for both couplers, being higher than the results predicted by simulations.

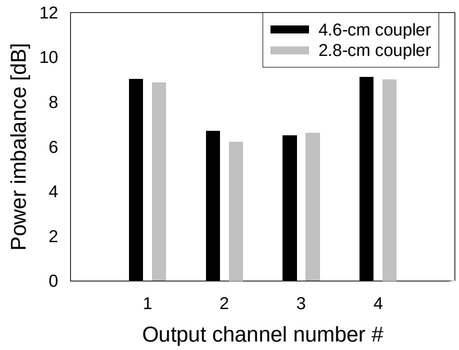

Figure 4: Normalized output power (with respect to the input) of the four channels of two 4 x 4 star couplers with coupler lengths of 46 and 28 mm.

V Conclusions

We have described and demonstrated a new method for designing compact multimode *1 x N* and *N x N* planar couplers. 3-D BPM simulations have shown that the couplers have low excess loss and low power imbalance and relaxed fabrication tolerances. The devices have been fabricated using low-cost polymer waveguide technologies. Preliminary optical characterization results have shown that the couplers have interesting properties for multimode fiber based LAN's.

References

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