

Design considerations for high packaging density optical bus array

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Abstract

In this paper, a crosstalk model is developed to study the packing density and interconnect distance limitations of an optical interconnect system employing polymer-based single-mode bus arrays. The upper limit of channel packing density (1250 channels/cm at interconnect distance of 5 cm) is determined for the first time using the crosstalk model, in which channel cross-coupling among an infinite number of waveguides is considered. Computer simulations are provided together with the proven experimental results. It is shown that there is a threshold of channel separation due to channel cross-coupling, which results in a tradeoff between channel packing density and interconnect distance. Waveguide dimension closer to the cutoff boundary of second mode (E_{12}^*) is preferred for an optimum design.

1. Introduction

Optical bus arrays are attractive for optical interconnect systems because of their low crosstalk, small propagation loss, and parallel operation with high packing density[1-4]. Optical bus arrays are used in massively parallel optical interconnects[5], integrated-optic star couplers[6], optical splitters and waveguide gratings[7-8]. Important criteria in determining the usefulness of optical bus arrays are their interconnect distance and packing density, which may be limited by the channel cross-coupling, and therefore has been investigated in some detail. The early investigation showed that the crosstalk noise due to channel cross-coupling must be smaller than -12 dB for incoherent light and -32 dB for coherent light using a 1-dB power penalty criterion at a bit-error-rate (BER) of 10^{-15} [9].

In this paper, the limitations on packing density and interconnect distance are investigated for the first time on a polymer-based single-mode bus array (PBSMBA). A crosstalk model is developed based on coupled-mode theory[10,11]. Also for the first time, an infinite number of cross-coupled buses is considered, and an exact simulated solution is presented together with the experimental results. It is shown that there is a threshold of acceptable packing density due to bus cross-coupling. For an optimum design, large waveguide dimension up to the cutoff boundary of second mode (E_{12}^*) is preferred. The analysis developed herein is applicable not only to the photolime gel PBSMBAs but also to single-mode optical bus arrays based on other materials.

2. Theory

The following describes the geometry used in our analysis. We consider an optical bus array using identical single-mode channel waveguides with uniform channel separation. The schematic of the device presented is shown in Fig. 1, where a single-mode channel waveguide array based on photolime gel polymer is employed as an optical bus array on a multi-chip-module (MCM) board[5]. The square single-mode channel waveguide is selected, with the channel width (a) equal to the channel depth (b). Here n_1 and $n_{2,5}$ are the refractive indices of the guiding layer and cladding layers, respectively. The cross section of a channel waveguide is also depicted in Fig. 1. The lateral index difference ($n_1 - n_{3,5}$) of up to 0.2 can be produced by the photo-induced index modulation, and the vertical index difference ($n_1 - n_4 \sim 0.01$) is due to the graded index effect of our polymer. $n_1 = 1.5$ and $n_2 = 1.0$ are the index of our polymer and index of air, respectively. The dimensions of a single-mode channel waveguide are dependent on all refractive indices and on the operating wavelength[4,5].

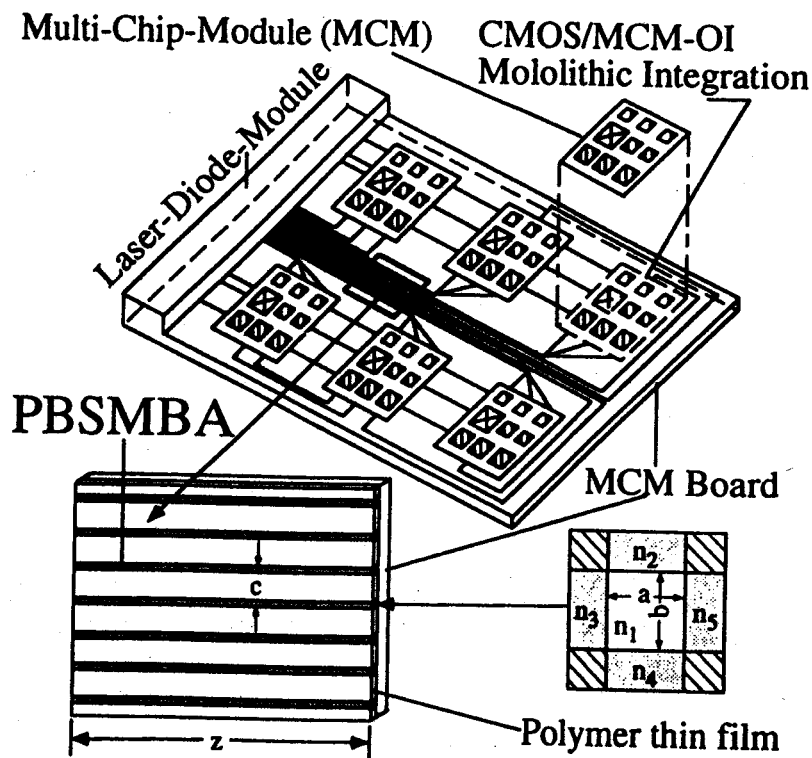


Figure 1. A schematic diagram of a MCM board using PBSMBA, where the cross section of a channel waveguide under consideration is also shown. PBSMBA: Polymer-based single-mode bus array.

Based on coupled-mode theory, the complex field in the n th channel obeys the equation[10,11]

$$\frac{E_n(z)}{dz} = -i\kappa E_{n-1}(z) - i\kappa E_{n+1}(z) - \frac{\alpha}{2} E_n(z) \quad n = 0, \pm 1, \pm 2, \dots \quad (1)$$

where n represents the n th channel waveguide, α is a single waveguide absorption coefficient, z is the

length of channel waveguide array and κ is the coupling coefficient between two adjacent waveguides. For a well-confined single-mode channel waveguide array with $a = b$, we have [12]

$$\kappa = -i \frac{\exp(-c/\xi)}{a\xi(2\pi n_1/\lambda - 2/\xi)}, \quad (2)$$

where λ is the operating wavelength, c is the channel separation, and $\xi = \xi_3 = \xi_5$ represents the penetration depth of the field components in cladding media 3 and 5. ξ is given by

$$\xi = \frac{A}{\pi} \left\{ 1 - \left[\frac{\pi A}{\pi a + 2A} \right]^2 \right\}^{-0.5}, \quad (3)$$

where $A = \frac{\lambda}{2} (n_1^2 - n_{3,5}^2)^{-0.5}$. Note that ξ is primarily determined by a , n_1 , n_3 and n_5 rather than b , n_2 and n_4 .

When the input energy for each channel is equivalent, the boundary condition of Eq. (1) is $|E_n(0)| = |E_0(0)| = E_0$. The solution to Eq. (1) for the center channel, can then be written as

$$E_0(z) = \{ E_0 J_0(2i\kappa z) + \sum_{n=1}^{\infty} [E_n(0)(-i)^n J_n(2i\kappa z)] \} \exp(-\frac{1}{2}\alpha z), \quad n \neq 0, \quad (4)$$

where J_0 and J_n represent the fundamental and n th order Bessel functions. The term $\exp(-\frac{1}{2}\alpha z)$ is due to waveguide propagation loss. The term $J_0(2i\kappa z)$ accounts for the signal remaining in its own channel, whereas higher order Bessel functions account for undesired crosstalk from other channels. Such crosstalk causes either noise increase or signal decrease. Note that the center channel experiences the most cross-coupling.

The crosstalk intensity to the center channel, based on Eq. (4), can thus be written as

$$I_{\text{coh}} = \left| \sum_{n=1}^{\infty} [E_n(0)(-i)^n J_n(2i\kappa z)] \right|^2 \exp(-\alpha z), \quad n \neq 0, \quad (5)$$

$$I_{\text{inc}} = |2E_0|^2 \left\{ \sum_{n=1}^{\infty} [J_n(2i\kappa z)]^2 \right\} \exp(-\alpha z), \quad (6)$$

for coherent and incoherent light, respectively. With coherent light sources, the phase relationship among all channels should be considered as well. To provide a conservative design criterion, we consider the worst case crosstalk where the cross-coupling noise from all other channels are in phase at the center channel and thus to give rise to the maximum noise level. With this condition, Eq. (5) becomes

$$I_{\text{coh}} = |2E_0|^2 \left\{ \left[\sum_{n=2m} J_n(2ikz) \right]^2 + \left[\sum_{n=2m+1} J_n(2ikz) \right]^2 \right\} \exp(\alpha z). \quad m = 1, 2, 3, \dots \quad (7)$$

The effect of waveguide propagation loss will be neglected in this paper because it only changes the power budget required rather than the crosstalk figure.

The simulations to be presented require that a specified signal-to-noise ratio ($R = 10 \log_{10} \left[\frac{I_s}{I_n} \right]$) be maintained at the output of a PBSMBA. In our case, we have $I_s = E_0^2$ and $I_n = I_{\text{coh}}$ or I_{inc} . These are given by equations (6) and (7) respectively. If the optical interconnect network uses binary pulse code modulation, the signal-to-noise ratio has to be large enough to obtain the required bit error rate (BER). For a BER of 10^{-15} , the required signal-to-noise ratio is 12 dB for using incoherent light sources and 32 dB for using coherent light sources[9]. The 20 dB difference in signal/noise ratio between using coherent light and using incoherent light is due to the effect of phase-to-intensity noise conversion in avalanche photodiodes. Such difference varies with the degree of coherence and is saturated at 20dB[9].

3. Simulation Results

Because of channel cross-coupling, the interconnect distance is strongly affected by the channel separation in a dense PBSMBA. Fig. 2 shows the tradeoff between channel length and channel separation based on Eqs. (6) and (7) for $n = \infty$. As indicated in Fig. 2, there is a threshold value of

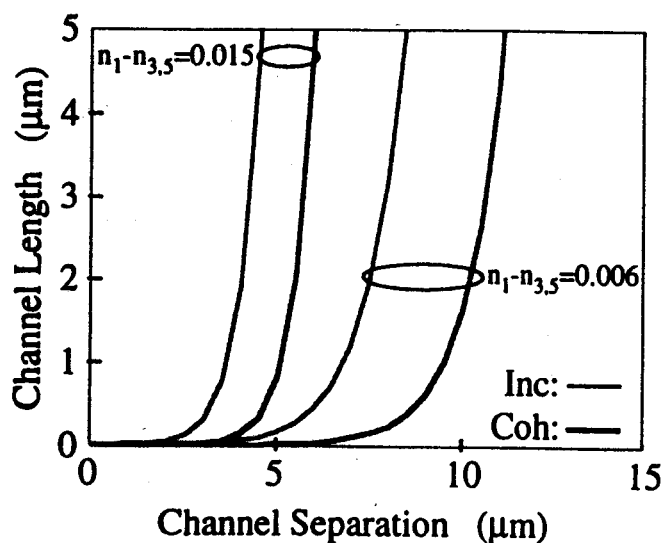


Figure 2. Channel length versus channel separation to ensure a BER of 10^{-15} , respectively, where $n_1 = 1.5$, $n_2 = 1.0$, and $\lambda = 0.6328 \mu\text{m}$ were assumed.

interconnect channel separation which decreases when increasing lateral index modulation ($n_1-n_{3,5}$). Also, coherent and incoherent light sources lead to significant differences in interconnect distance for the same system performance. To obtain 5 cm interconnect distance, with a waveguide dimension of $a = b = 2 \mu\text{m}$ and $n_1-n_{3,5} = 0.006$, it may be necessary to separate the waveguides up to $12 \mu\text{m}$ (six times of channel dimension). For more favorable lateral index modulation of $n_1-n_{3,5} = 0.015$ (the cutoff condition of a multimode channel waveguide), the required channel separation is $6 \mu\text{m}$ (as shown in Fig. 2 for coherent light). In other words, Fig. 2 indicates that the upper limit to packing density is 1250 channels/cm for a 5.0 cm long PBSMBA.

In order to find the optimum waveguide dimension, the channel separation versus waveguide dimension in a single-mode channel waveguide array was theoretically determined based on Eqs. (6) and (7) for $n = \infty$, and the results plotted in Fig. 3. It indicates that larger waveguide dimension, i.e., up to the cutoff boundary of second mode ($\beta_{1,2}$), gives rise to a smaller channel separation when the lateral refractive index difference is fixed. This is because that the large waveguide dimension decreases the evanescent tail and thus increases the confinement effect. Consequently, the channel packing density can be increased or fixed while enlarging the single-mode waveguide dimension. Such a result is very useful for designing a dense single-mode channel waveguide array, where large waveguide dimension is always preferred for both coupling and fabrication. The physical parameters of a symmetric square single-mode waveguide array used in the calculation, can be found in Fig. 3. The signal-to-noise ratio was set at 32 dB for coherent light and 12 dB for incoherent light.

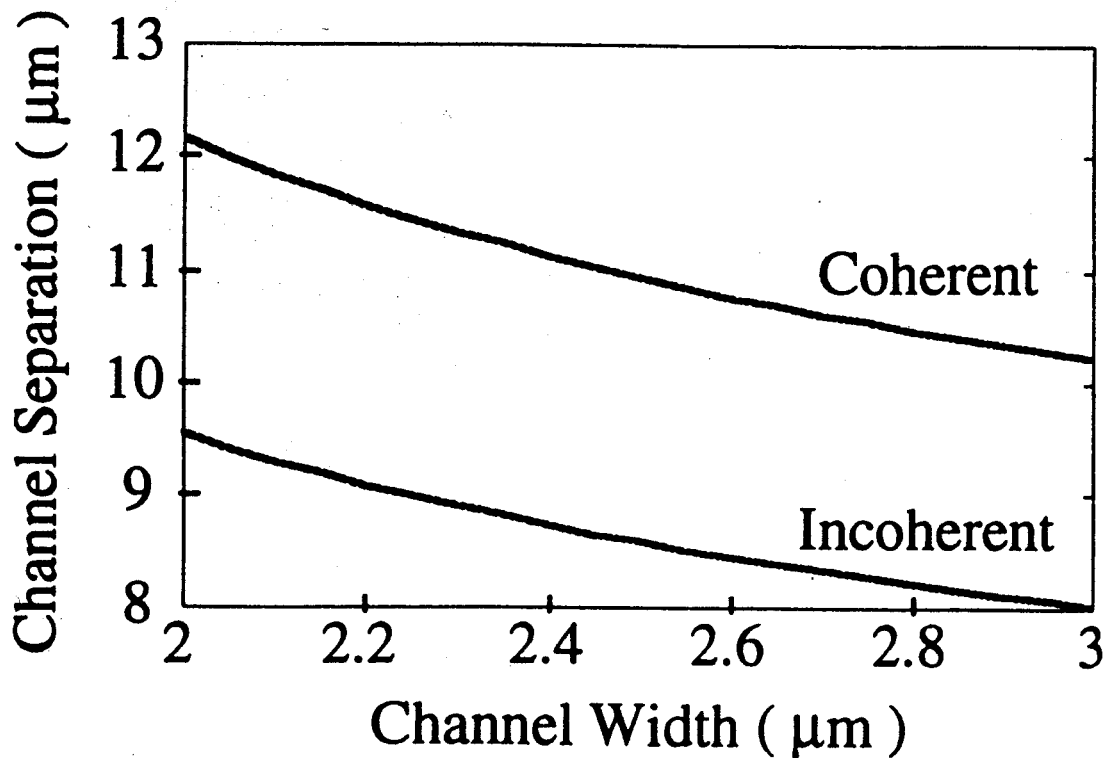


Figure 3. Channel separation versus channel dimension based on Eqs. (6) and (7). $z = 5 \text{ cm}$, $a = b = 2 \mu\text{m}$, $n_1 = 1.5$, $n_2 = 1.0$, $n_1-n_4 = 0.01$ and $n_1-n_{3,5} = 0.006$ at $\lambda = 0.6328 \mu\text{m}$ were assumed.

4. Experimental Results

To evaluate the accuracy of the formulae developed, a 100 channel, 5 cm long single-mode waveguide array was fabricated with channel separation of $c = 8 \mu\text{m}$ and channel width of $a = 2 \mu\text{m}$. Waveguide indices $n_1 = 1.5$ and $n_1 - n_{3,5} = 0.006$ were experimentally confirmed using the IWKB method[13]. Fig. 4 is a photograph of the near field pattern of optical throughput of such a PBSMBA. In the experiment, two HeNe laser beams ($\lambda = 0.6328 \mu\text{m}$) with nearly uniform intensities ($I_o/I_o = 0.85/0.95$) were coupled into the two center channel waveguides, respectively. There was no optical wave launched into the other channels at the input end, which mimics the situation of power-off with respect to the two power-on center channels in an optical binary modulation system. As indicated in Fig. 4, significant power was coupled into the side channels. It shows that the crosstalk noise due to the channel cross-coupling may seriously affect the system performance and must be considered in designing a dense PBSMBA.

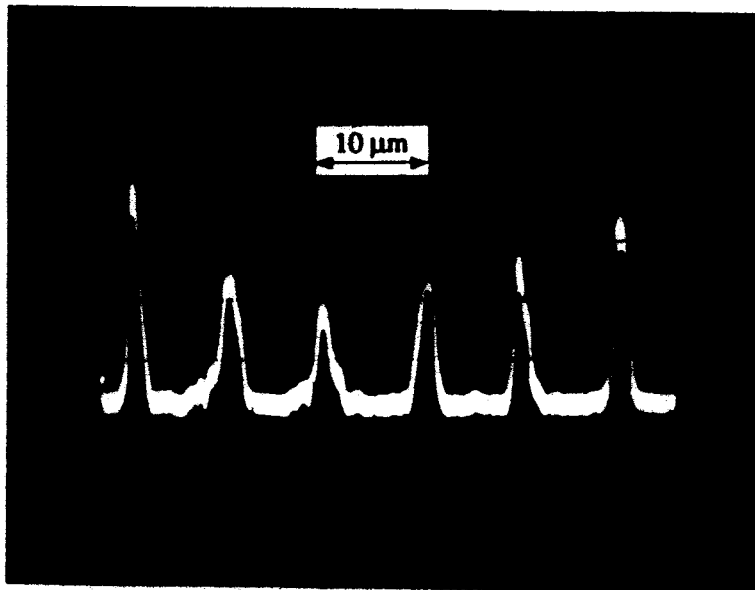


Figure 4. Photograph of experimental result for multiple channel cross-coupling in a PBSMBA.

Fig. 5(a) is a plot of the theoretical calculation of longitudinal intensity distribution in a PBSMBA based on Eq. (5) using the experimental parameters of Fig. 4. Input light waves with equal intensity and phase were assumed at the input end of the two center channels. Fig. 5(b) shows the transverse intensity distribution of the six center waveguides at the propagation distance of $z = 5 \text{ cm}$. The optical intensity in each channel waveguide is equivalent to Gaussian distribution with a beam waist $w = (a + \xi)$. The slight mismatch between the experimental and calculated profile for channel 2 is due to the waveguide non-uniformity.

Thin film polymer-based channel waveguide arrays have the advantage of providing linear and curved optical interconnections with high packing density (1250/channel/cm) at small waveguide propagation loss of $\sim 0.1 \text{ dB}$ and high transmission speed (60 GHz)[5,14]. It is the only guided wave interconnection device that is technologically mass producible by compression-molded technology[4]. Also the graded index property, discovered in photolime polymer-based thin film waveguides, makes

such devices particularly attractive to be fabricated on high-index and/or high loss substrates, such as Si, GaAs chip and PC board[5].

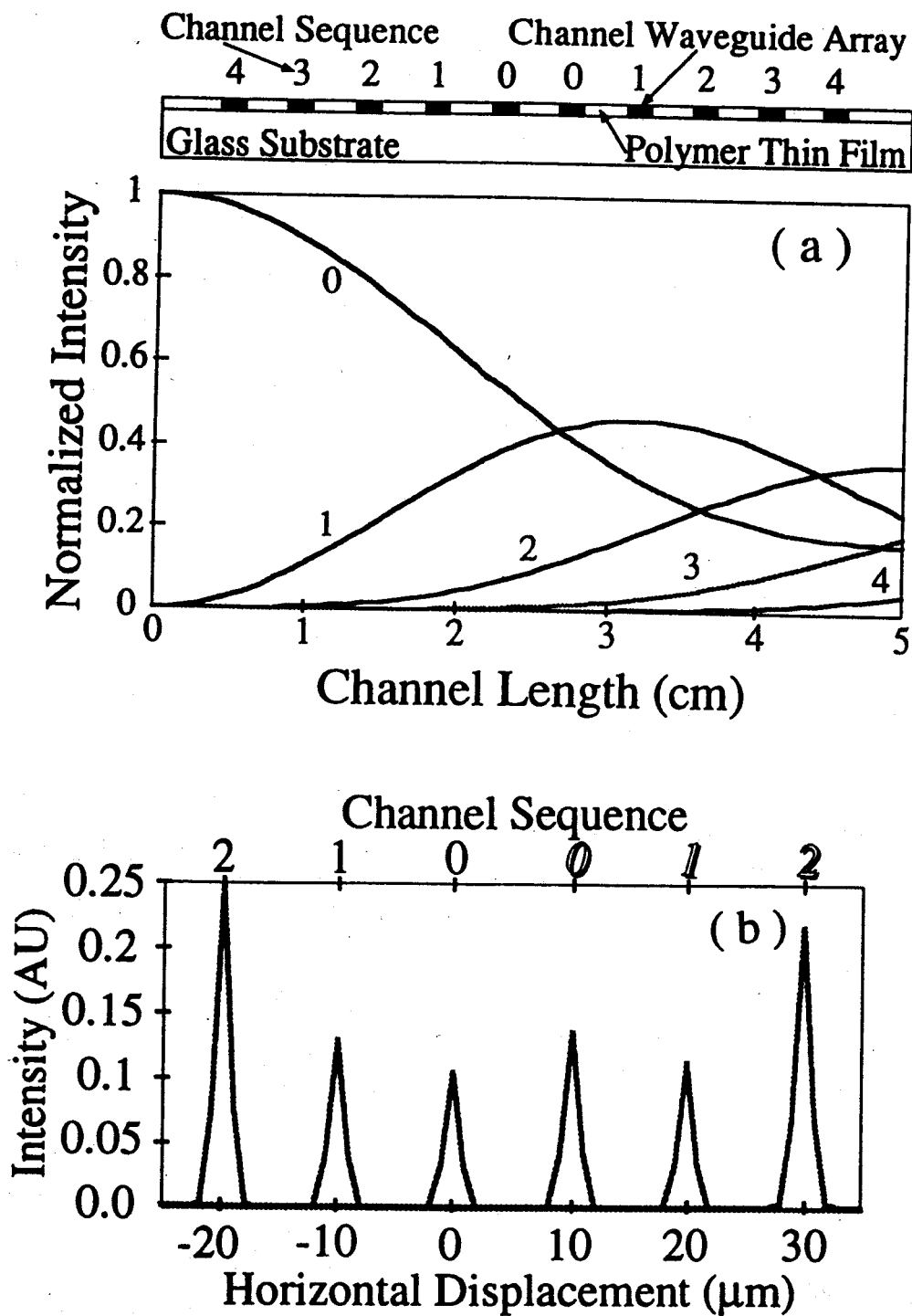


Figure 5. (a) The intensity distribution in a PBSMBA based on Eq. (7) using the experimental parameters of Fig. 4, where $n = \infty$ was assumed. (b) The transverse intensity distribution at $z = 5$ cm using the experimental parameters of Fig. 4.

5. Concluding Remarks

In summary, a crosstalk model has been developed to study the system limitations on optical interconnects employing PBSMBAs. The upper channel packing density limit was found to be 1250 channels/cm for a 5 cm interconnect distance. This represents the first determination of packing density limit using an exact solution of the coupled-mode equations while considering channel cross-coupling among infinite number of waveguides. Computer simulations were presented together with experimental results. It was shown that there is a threshold of channel separation because of channel cross-coupling, which results in a tradeoff between channel packing density and interconnect distance. To reduce the threshold of channel separation, high lateral index modulation is needed. Also based on the analysis, large waveguide dimension (up to the cutoff boundary of second mode ($\beta_{1,2}$)), is preferred for an optimum design in a dense PBSMBA. The analysis developed herein is applicable not only to the photolime gel PBSMBAs but also to single-mode channel waveguide bus arrays based on other materials.

6. Acknowledgement

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7. References

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