# System Limitations Due to Channel Cross-coupling in a Highly Parallel Polymer-Based Single-mode Channel Waveguide Array

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## 1. ABSTRACT

Interconnection length and packaging density are important parameters in channel-waveguide-based photonic integrated circuits. In this paper, a multiple channel crosstalk model is developed and then applied, together with experimental results, to study the minimum channel separation and maximum channel length in a highly parallel single-mode channel waveguide array (SMCWA). Further investigation of the tradeoff between channel packaging density and interconnection length due to channel cross-coupling indicates that, in order to obtain a desirable interconnection length, it is often necessary to separate the waveguides in the array on the order of several (3 ~ 7) channel dimensions. For a given waveguide and cladding index, it is found that SMCWA waveguide dimensions should be close to the cutoff dimensions of the second-mode in order to obtain an optimal confinement factor. The maximum packaging density of an SMCWA using coherent light sources is shown to be different from that using incoherent light sources. Using a 32 dB required signal-to-noise ratio criterion for coherent light sources and a 12 dB criterion for incoherent light sources, it is shown that the packaging density in a polymer-based SMCWA with a channel length of 2.0 cm, a core index $n_1 = 1.5$, and a lateral $\Delta n \sim 0.01$ to 0.001 ranges from 300-750 channels/cm for coherent light sources and from 400-950 channels/cm for incoherent light sources. Further experimental work is conducted to confirm the accuracy of the theory presented herein.

## 2. INTRODUCTION

Replacement of electrical interconnects with optical interconnects requires a medium through which optical signals can be routed from transmitters to receivers. For this purpose, two available choices are optical fibers and thin film waveguides. For machine-to-machine optical interconnects, optical fibers are the medium of choice. For interconnection scenarios such as backplane, intermodule, and intramodule, thin film channel waveguides are the major tools under intensive investigation[1-5]. In addition, thin film channel waveguide arrays are important building blocks for many optoelectronic interconnection systems[6-9], since they are the only guided-wave interconnection devices that can be lithographically mass produced.

Two key criteria determining the usefulness of such interconnects are the interconnect length and packaging density. The channel length and density of waveguide arrays may be limited by many reasons, including propagation losses and crosstalk caused by stray light from scattering, reflection, and diffraction . It is reported[10,11] that the crosstalk noise between neighboring waveguides must be smaller than -12 dB for incoherent light sources and -32 dB for coherent lights source in order to provide an optical interconnection system with a extinction ratio of 20, 1-dB power penalty and a bit-error-rate(BER) of $10^{-15}$. Based on our analysis and experimental results, the coupling-induced crosstalk between channel waveguides gives rise to major limitations in both interconnect length and packaging density of an SMCWA. In an optical interconnect system using a polymer-based SMCWA with refractive index $n_1 = 1.5$ and lateral index difference $\Delta n = (n_1-n_{3,5})/n_1 = 0.001\sim0.01$ (see Fig. 1), our results indicate that the channel separation has to be larger than several channel dimensions, in the range of 3 to 7, to provide the required signal/noise ratio.

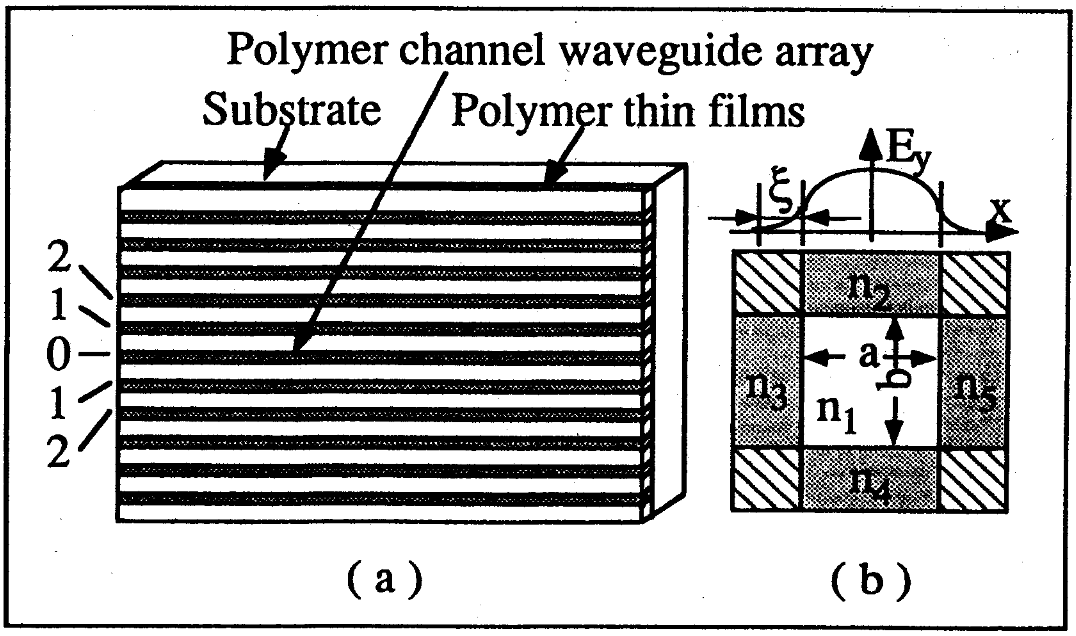

Figure 1. (a) A schematic diagram of a polymer-based channel waveguide array. (b) The cross section of a channel waveguide under consideration. In this paper, all the calculation is conducted with a = b.

In this paper, a crosstalk model that considers cross-coupling between an infinite number of parallel waveguides is employed to relate the maximum interconnect length and packaging density to waveguide parameters of an SMCWA. The tradeoff between minimum channel separation(MCS) and maximum channel length(MCL) is determined with crosstalk noise as a parameter. This noise is generated by the cross-coupling between light waves propagating in different channel waveguides[12-14]. Our crosstalk model yields an optimum design to obtain high packaging density and long interconnection length for an SMCWA. The effects of light source coherence on MCS and MCL are discussed for both the multiple channel cross-coupling and receiver phase-to-intensity noise conversion mechanisms. Using a photolime gelatin based SMCWA[3-5], channel packaging density limitations due to channel cross-coupling were experimentally observed and studied, confirming the theory presented herein.

## 3. WAVEGUIDE DIMENSIONS

In the following analysis, we consider an optical interconnection system using identical single-mode channel waveguides with uniform channel separation. For simplicity, the symmetric single-mode channel waveguide is selected, with a channel width a equal to b and $n_1 > n_2, n_3, n_4, n_5$. Here $n_1$ and $n_{2\text{-}5}$ are the refractive indices of the guiding layer and cladding layers, respectively. Fig. 1(a) shows a schematic diagram of a cross-link induced linear channel waveguide array on photolime gel. The cross section of a channel waveguide is depicted in Fig. 1(b). The lateral index difference $(n_1-n_{3,5})$ is created by the photoinduced 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 assumed in this paper. The dimensions of a single-mode channel waveguide are dependent not only on the refractive indices of the guiding medium and cladding layers, but also on the operating wavelength[12]. As the optical wavelength becomes shorter and the relative index difference $\Delta n \equiv (n_1 - n_{3,4,5})/n_1$ increases, single-mode waveguide dimensions shrink. However, practical considerations limit the miniaturization of waveguides. For example, it is very difficult to achieve efficient coupling between a light source and a channel waveguide with a cross section smaller than the beam waist of the $TEM_{00}$ mode of a laser. Single-mode channel waveguides with dimensions close to the cutoff boundary of the second mode are preferred for high packaging density in an SMCWA design. The required waveguide dimensions can be calculated once the relative index difference had been determined. Note that the channel density is determined by the sum of channel width and channel separation.

## 4. THE CROSS-COUPLING BETWEEN MULTIPLE CHANEL WAVEGUIDES

For an SMCWA shown in Fig. 1, the optical wave propagating through each channel waveguide may couple out to adjacent channels. In many cases, this effect results in a major limitation on MCS and MCL. The coupling coefficient between two fundamental TE waves, propagating through two neighboring single-mode channel waveguides, can be approximated as[12],

$$|\kappa| = \frac{1}{a\xi k_z} \exp(-c/\xi), \qquad (1)$$

where $k_z = ( 2\pi n_1/\lambda - 2/\xi )$ for a symmetric square channel waveguide, $\lambda$ is the operating wavelength, c is the channel separation, and $\xi = \xi_3 = \xi_5$ represent the penetration depths of the field components in cladding media 3 and 5. For single-mode operation, $\xi$ is given by

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

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

We assume that the electrical field in each channel has equal and normalized amplitude. Based on the coupled mode theory[13], the maximum cross-coupling intensity to the center channel (see Fig. 1) can be written as

$$I_{coh} = \{2\sin(|\kappa|z) + 2\sin^2(|\kappa|z) + 2\sin^3(|\kappa|z) \ldots + 2\sin^n(|\kappa|z)\}^2, \qquad (3)$$

and

$$I_{inc} = 2\{\sin^2(|\kappa|z) + \sin^4(|\kappa|z) + \sin^6(|\kappa|z) \ldots + \sin^{2n}(|\kappa|z)\}, \qquad (4)$$

or coherent and incoherent light, respectively. 2n+1 is the total number of waveguides. In Equations (3) and (4), z is coupling length, i.e., length of the channel waveguide. Note that coherent light ources are defined as sources whose linewidths ($\Delta\nu$) and inter-source frequency spacing are much maller than the electrical bandwidth(BW) of the receiver[11]. Equations (3) and (4) were obtained by ssuming that

(a) the guided-waves propagating in each channel could couple into the center channel through adjacent channels, and
(b) all guided-waves coupled into the center channel were in phase and would not couple back to other channels.

These assumptions represent the worst case condition for crosstalk and thus impose the most stringent conditions for the design of an SMCWA. Propagation losses are neglected in equations (3) and (4) because they do not contribute to crosstalk.

For coupling conditions where $|\kappa|z << 1$ and $n \to \infty$, equations (3) and (4) can be written as

$$I_{coh} = 4 \left[ \frac{|\kappa|z}{1 - |\kappa|z} \right]^2 , \text{ and} \tag{5}$$

$$I_{inc} = 2 \frac{[|\kappa|z]^2}{[1 - |\kappa|z]^2} . \tag{6}$$

Equations (5) and (6) indicate that the optical intensity coupled into the center channel from other channels is a function of coupling coefficient and channel length. By substituting Eq. (1) into Equations (5) and (6), the minimum channel separation can be obtained as,

$$c_{coh} = - \xi \ln \left[ \frac{a\xi k_z}{z} \frac{2(I_{coh})^{0.5} - I_{coh}}{4 - I_{coh}} \right] , \text{ and} \tag{7}$$

$$c_{inc} = - \xi \ln \left[ \frac{a\xi k_z}{z} \left( \frac{I_{inc}}{2 + I_{inc}} \right)^{0.5} \right] . \tag{8}$$

Equations (7) and (8) are very useful in designing SMCWAs. If all the parameters of an SMCWA, including waveguide indices, dimensions, and signal wavelength, are defined, the minimum channel separation can be obtained by setting a desired crosstalk noise criterion, $I_{con}$ and $I_{inc}$.

The crosstalk noise criteria, $I_{coh}$ and $I_{inc}$, can be determined based on system performance from the signal/noise ratio required at the output end of an SMCWA , defined as $R = 10 \log_{10} [ \frac{I_s}{I_n} ]$. In our case, using normalized intensity, we have $I_s = 1$ and $I_n = I_{coh}$ or $I_n = I_{inc}$, which are given by Equations (3) and (4) respectively. If binary pulse code modulation is employed in an optical interconnection network, the signal/noise ratio has to be large enough to obtain the required bit error rate. At a BER of $10^{-15}$, the required signal/noise ratio is 12 dB for incoherent light sources and 32 dB for coherent light sources assuming an extinction ratio of 20, laser linewidth of 2 GHz, electrical bandwidth of 10 GHz and a 1-dB power penalty criterion. The 20 dB difference in required signal/noise ratio between coherent and incoherent light sources is due to the effects of phase-to-intensity noise conversion in avalanche photodiodes. This difference varies with the degree of coherence($\frac{BW}{\Delta\nu}$) and saturates at ~20 dB[10,11].

The minimum channel separation versus the signal/noise ratio, based on equations (7) and (8), is plotted in Fig. 2. Two symmetric square SMCWAs were selected with channel widths of 3 μm and 10 μm, and relative index differences (Δn) of 0.01 and 0.001, respectively. As indicated in Fig. 2, the coherence of the light source results in a different minimum channel separation. Furthermore, because the signal/noise ratio imposed by the optical interconnect system using a coherent light source is much higher than that using an incoherent light source, the minimum channel separation may vary up to few channel widths when optical waves with different degrees of temporal coherence are employed. For example, using a 1-dB power penalty criterion at a BER of $10^{-15}$, the signal to noise ratio needed at the output end of SMCWA is 12 dB for incoherent light and 32 dB for coherent light as shown in Fig. 2. The figure also indicates that different waveguide dimensions, corresponding to a different Δn value, should require a different channel separation to ensure a desired signal/noise ratio. Based on this data, waveguide packaging densities are found to be in the range of 300-750 channels/cm for coherent light sources, and of 400-950 channels/cm for incoherent light sources.

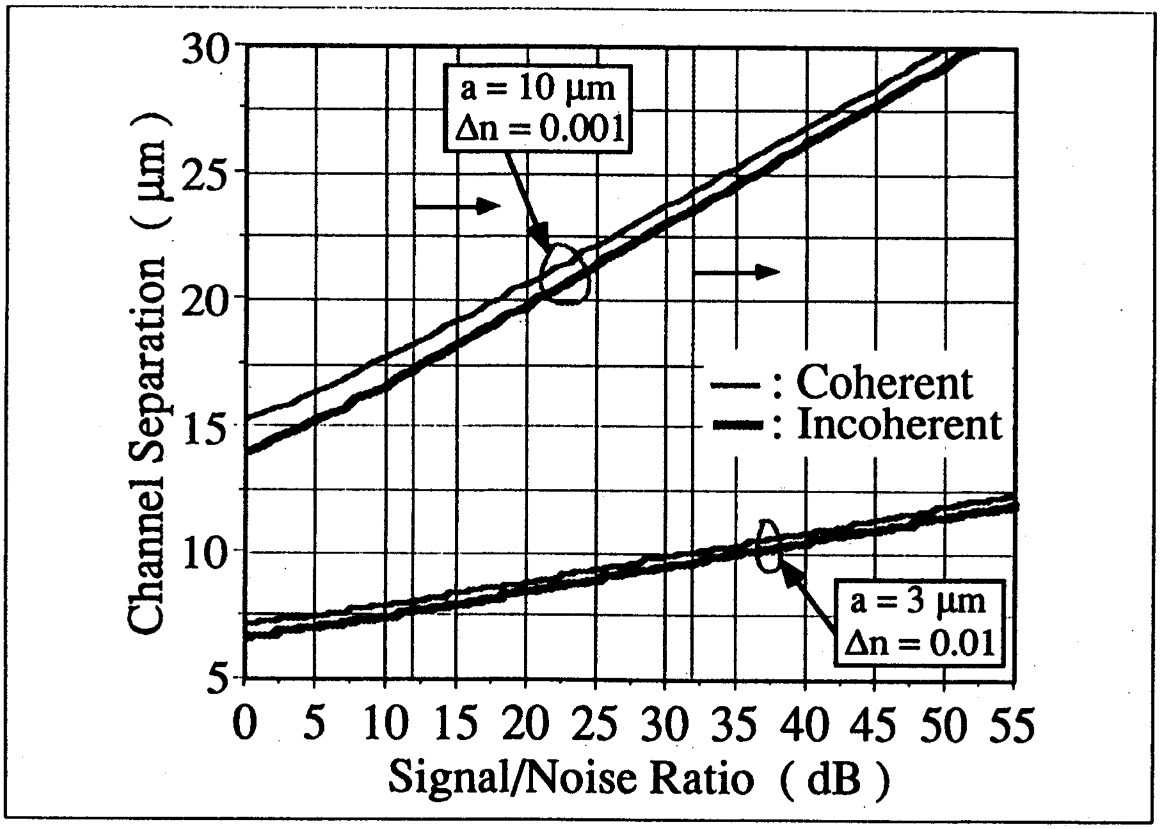

Figure 2. Minimum channel separation versus signal/noise ratio based on Eqs. (7) and (8). $z = 2$ cm, $n_1 = 1.5$, $n_2 = 1.0$, $\Delta n = 0.01$ for $a = 3$ μm and $\Delta n = 0.001$ for $a = 10$ μm at $\lambda = 1$ μm were assumed.

In order to find the optimum design rule, the minimum channel separation versus waveguide dimension in an SMCWA was determined based on equations (7) and (8) and is plotted in Fig. 3. It indicates that, for a given relative index difference, a single-mode channel waveguide with dimensions close to the cutoff boundary of the second mode is preferred for high packaging density in an SMCWA design. The relationship between MCS and penetration depth is also shown in this figure, with channel width ranging from 1.75 μm to 3.75 μm for single-mode operation. Minimizing the evanescent tail, and thus maximizing the confinement factor, plays a paramount role in high packaging density channel waveguide arrays. Note that this interesting result is pivotal for designing waveguide grating wavelength routers, where the high packaging density, long channel length and large waveguide dimensions are all necessary[9]. The physical parameters of the symmetric square SMCWA used in the calculation can be found in Fig. 3. The signal/noise ratio criteria were set at 32 dB for a coherent light source and 12 dB for the an incoherent source.

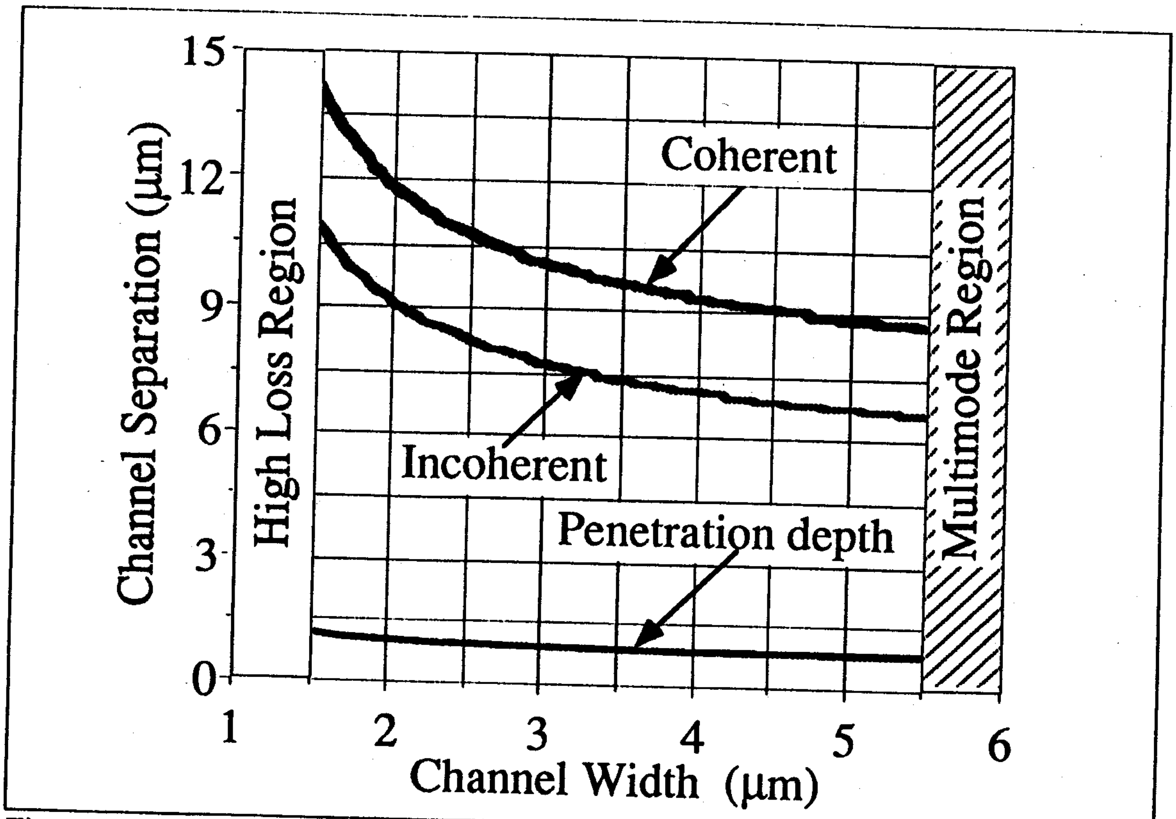

Figure 3. Minimum channel separation versus channel width to ensure a minimum of 32 dB signal/noise ratio based on Eqs. (7) and (8). The penetration depth $\xi$ is also shown in the figure. $z = 2$ cm, $n_1 = 1.5$, $n_2 = 1.0$, and $\Delta n = 0.01$ for $a = 3$ μm at $\lambda = 1$ μm were assumed.

The packaging density of an SMCWA with a given crosstalk figure is primarily determined by the index difference between the waveguide guiding layer and cladding layer. The larger the relative index difference, the smaller channel separation will be. The minimum channel separation versus the relative index difference, based on equations (7) and (8), is plotted in Fig. 4. As indicated in this figure, a large relative refractive index is preferred for obtaining densely packed SMCWAs. The relationship between MCS and penetration depth is also shown in this figure with $\Delta n$ ranging from 0.003 to 0.013 for single-mode operation. The relative refractive index difference of our polymer is adjustable up to 0.2[3], corresponding to $\Delta n = 0.13$ ($n_1 = 1.5$). However, if the refractive index difference is too high, the dimensions of a single-mode channel waveguide will be very small, (less than 1 μm for $\Delta n = 0.1$), which can create light source-to-waveguide coupling difficulties. The physical parameters of the symmetric square SMCWA used in the calculation can be found in Fig. 4. Again, the signal/noise ratio criteria were set at 32 dB for coherent light sources and 12 dB for incoherent sources.

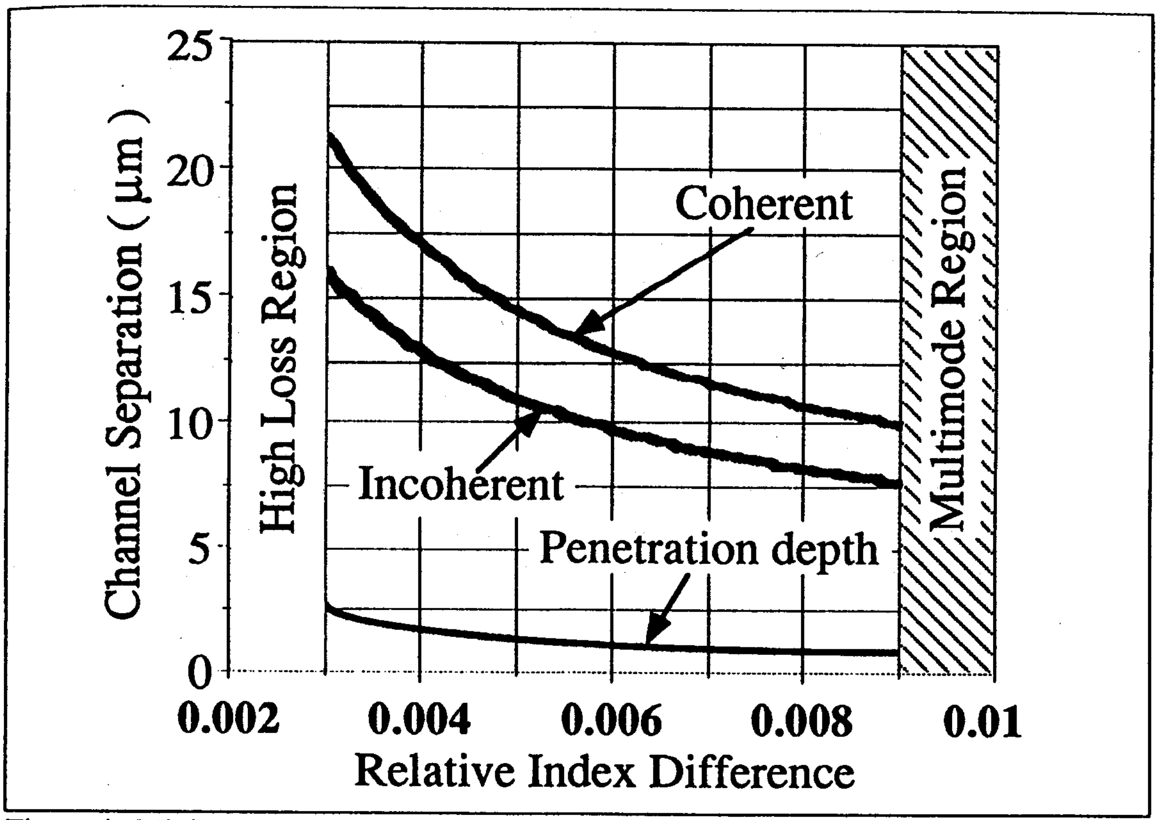

Figure 4. Minimum channel separation versus relative index difference to ensure a minimum of 32 dB signal/noise ratio based on Eqs. (7) and (8). The penetration depth $\xi$ is also shown in the figure. $z = 2$ cm, $n_1 = 1.5$, $n_2 = 1.0$, and $\Delta n = 0.01$ at $\lambda = 1.0$ µm were assumed.

If all related waveguide parameters are defined, equations (7) and (8) can be used to derive the maximum channel length and packing density:

$$z_{coh} = a\xi k_z \left[\frac{2(I_{coh})^{0.5} - I_{coh}}{4 - I_{coh}}\right] \exp\left(\frac{c}{\xi}\right), \tag{9}$$

and

$$z_{inc} = a\xi k_z \left[\frac{I_{inc}}{2 + I_{inc}}\right]^{0.5} \exp\left(\frac{c}{\xi}\right). \tag{10}$$

These two equations indicate that the channel length increases exponentially with the channel separation for a fixed $\Delta n$. The longer the channel length, the larger the channel separations has to be in order to ensure a desired signal/noise ratio. This demonstrates the tradeoff between channel packaging density and interconnect length.

The relationship between maximum channel length and minimum channel separation is illustrated in Fig. 5, based on Equations (9) and (10), which shows the fact that the maximum channel length is strongly affected by channel separation in a dense SMCWA. As indicated in this figure, there is a threshold value for channel separation required to obtain an optimized optical interconnection length using an SMCWA. Larger waveguide dimensions, corresponding to a smaller Δn, give rise to a higher threshold value for channel separation. To obtain the required optical interconnection length with a = 3 µm, Δn = 0.01 and a = 10 µm, Δn = 0.001 (at $n_1 = 1.5$), it would be necessary to separate the waveguides at least 3 times the channel width (see Fig. 5). In a dense SMCWA, there is a significant difference between the maximum interconnection lengths of systems employing coherent and incoherent light sources, as shown in Fig. 5. In spite of the limitations caused by the cross-coupling between channel waveguides, very long interconnection lengths (~50 cm) with high packaging density (~650 channel/cm) can be achieved by employing polymer-based SMCWAs.

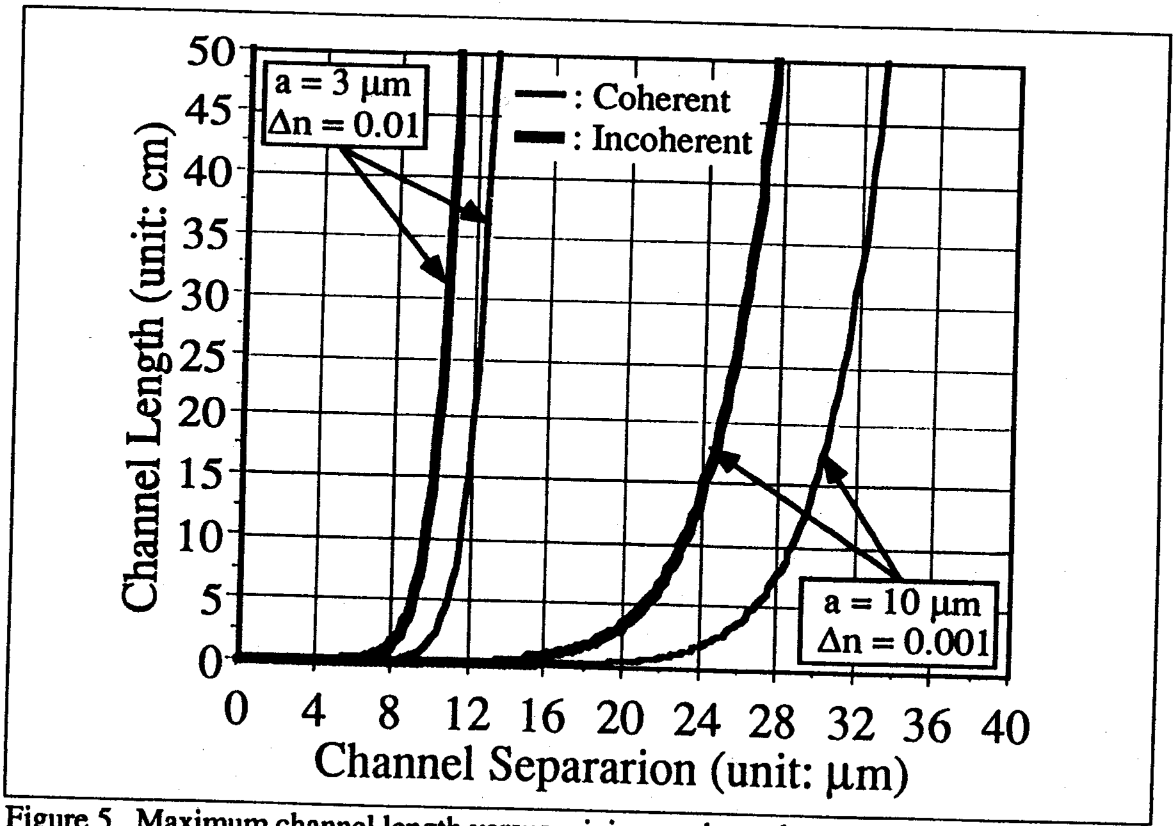

Figure 5. Maximum channel length versus minimum channel separation to ensure a 32 dB and 12 dB signal/noise ratio for coherent light source and incoherent light source based on Equations (9) and (10), respectively. ($n_1 = 1.5$, $n_2 = 1.0$, and $\lambda = 1$ µm were assumed.)

## 5. EXPERIMENTAL RESULTS

To verify the packaging density limitations caused by channel cross-coupling in a dense SMCWA, a cross-link induced linear SMCWA on graded index photolime gelatin was fabricated and tested. The fabricated SMCWA had a uniform channel separation of 8 µm, channel width of 2 µm and channel length of 2 cm. An $n_1 = 1.5$, ($n_2 = 1.0$), $\Delta n = 0.004$, $n1 - n_4 \approx 0.01$ and propagation loss about 0.1 dB/cm were experimentally determined[3,15]. A HeNe laser with uniform intensity operating at a wavelength of 0.6328 µm was coupled into the SMCWA. Because of channel cross-coupling, significant optical power was transferred among the waveguides, resulting in a non-uniform intensity distribution at the output end of the SMCWA. Such effects give rise to undesired optical crosstalk, which can set major limitations on system performance.

To further identify and evaluate the multiple channel cross-coupling in the experiment, three optical beams from a HeNe laser ($\lambda = 0.6328$ µm) with uniform intensity were coupled into the three center waveguides of the array. No optical power was launched into any of the other channels at the array input. Fig. 6 is the image of mode profile of each channel obtained at the output end. The cross-coupling among 5 channels is clearly shown in the figure. As indicated in the Fig. 6, significant optical power (up to 20%) was transferred into the outer channels and the center channel at the output end of the channel waveguide array. Fig. 7(a) and 7(b) are plots of the calculated intensity distribution in an SMCWA, where three input light waves with same intensity were assumed at the input ends of three center channels. The calculation assumes $z = 2$ cm, $n_1 = 1.50$, $\Delta n = 0.004$, $a = 2$ µm, and $c = 8$ µm. The optical intensity in each channel waveguide is further assumed to have Gaussian distribution with a beam waist $w = (a + \xi)$. The agreement between Figs. 6 and 7 is obvious. Note that Fig. 7 was obtained by modifying Eq. (3) on each channel while considering the energy conservation among all the channels.

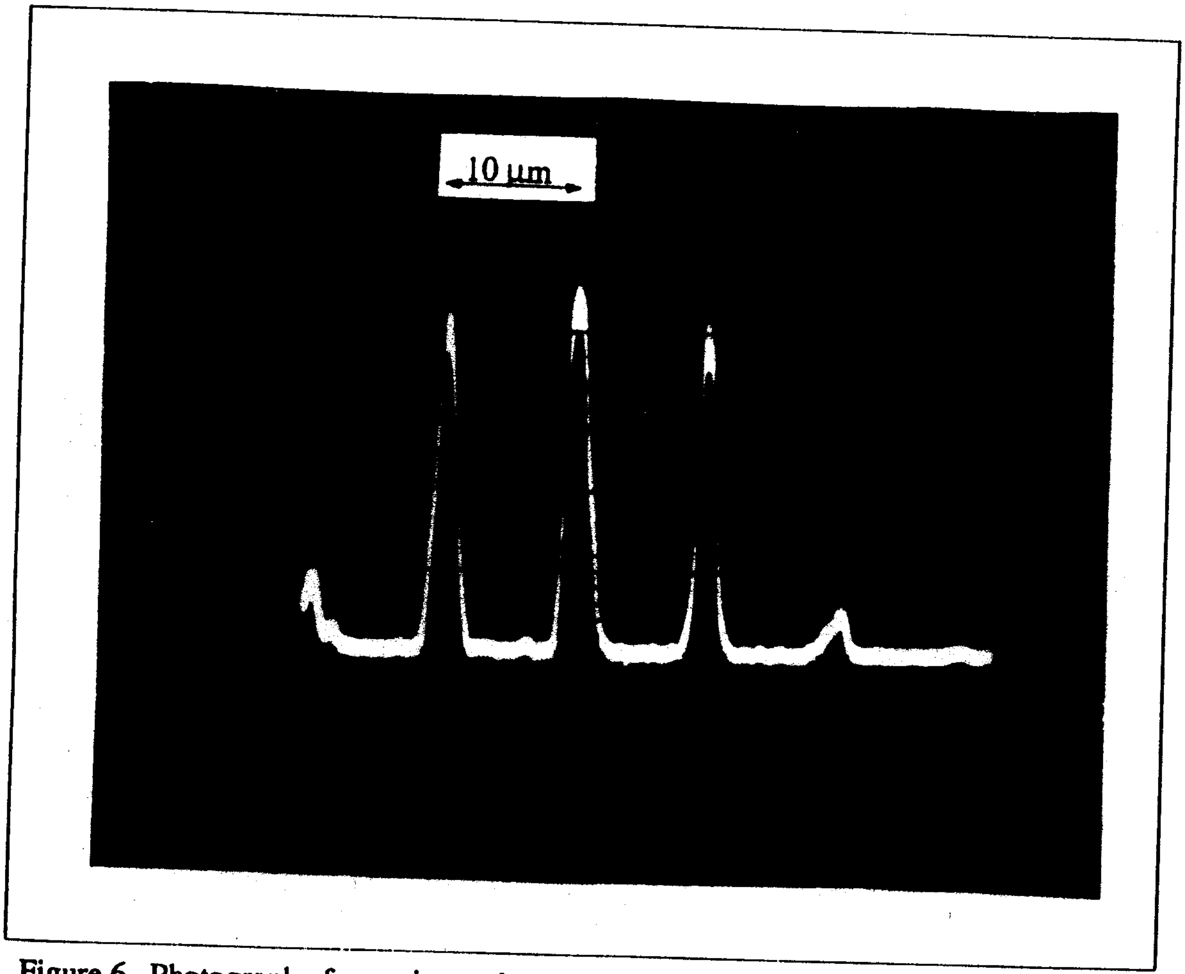

Figure 6. Photograph of experimental result for multiple channel cross-coupling ($n = 3$) in a polymer based SMCWA with $n_1 = 1.5$, $n_2 = 1.0$, $\Delta n = 0.004$, $a = 2$ µm, $c = 8$ µm, and $z = 2$ cm at $\lambda = 0.6328$ µm.

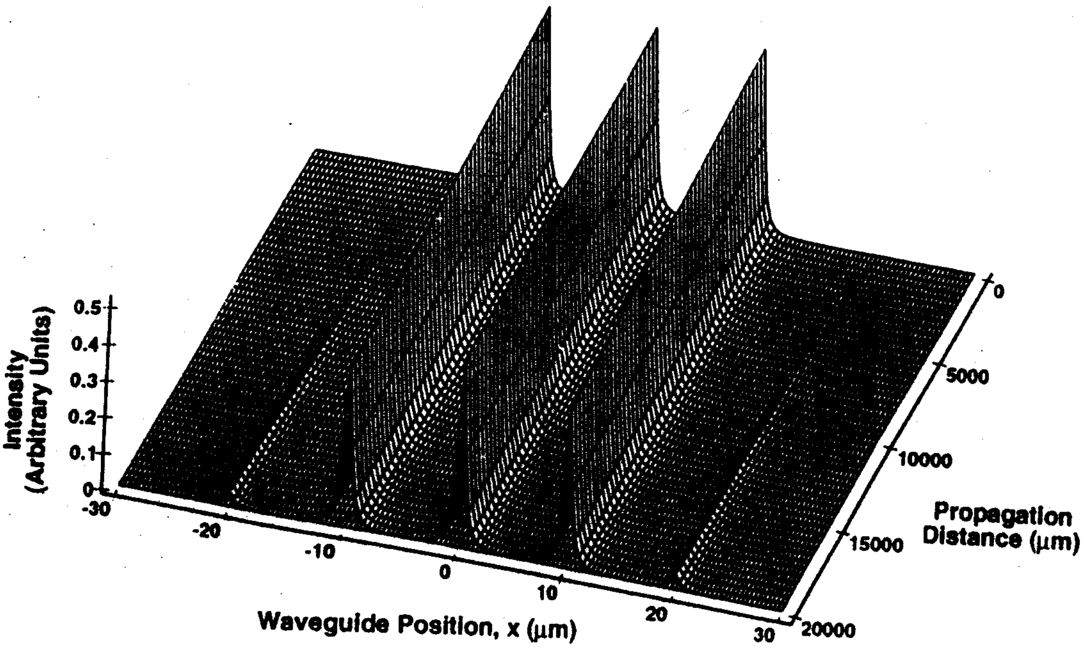

Figure 7. The 3D plot of the calculated intensity distribution in an SMCWA, using experimental parameters of Fig. 6.

To ensure a required interconnect length, the channel separation in an SMCWA has to be large enough to avoid significant channel cross-coupling. Therefore, in designing an SMCWA, it is necessary to find the minimum channel required separation so that multiple channel crosstalk can be minimized and a desired signal/noise ratio can be achieved for the desired interconnection length. Fig. 8 is a plot of maximum channel length versus the signal/noise ratio for several values of channel separation, based on Equation (9), using the experimental parameters. The interconnect length of the SMCWA that we fabricated must be limited to about 0.1 cm in order to ensure a 32 dB signal/noise ratio, as indicated in this figure. To have channel length longer than 5 cm while maintaining signal/noise ratio above 32 dB, the minimum channel separation must be increased from 8 μm to 12 μm. Therefore, the channel packaging density of the SMCWA fabricated in our experiment could have been up to 700 channels/cm with channel lengths close to 5 cm and a signal/noise ratio above 32 dB, if the channel separation was increased to 12 μm. The effect of waveguide propagation losses is not considered in this paper. Such losses will change the system power budget rather than the cross-talk effect considered herein.

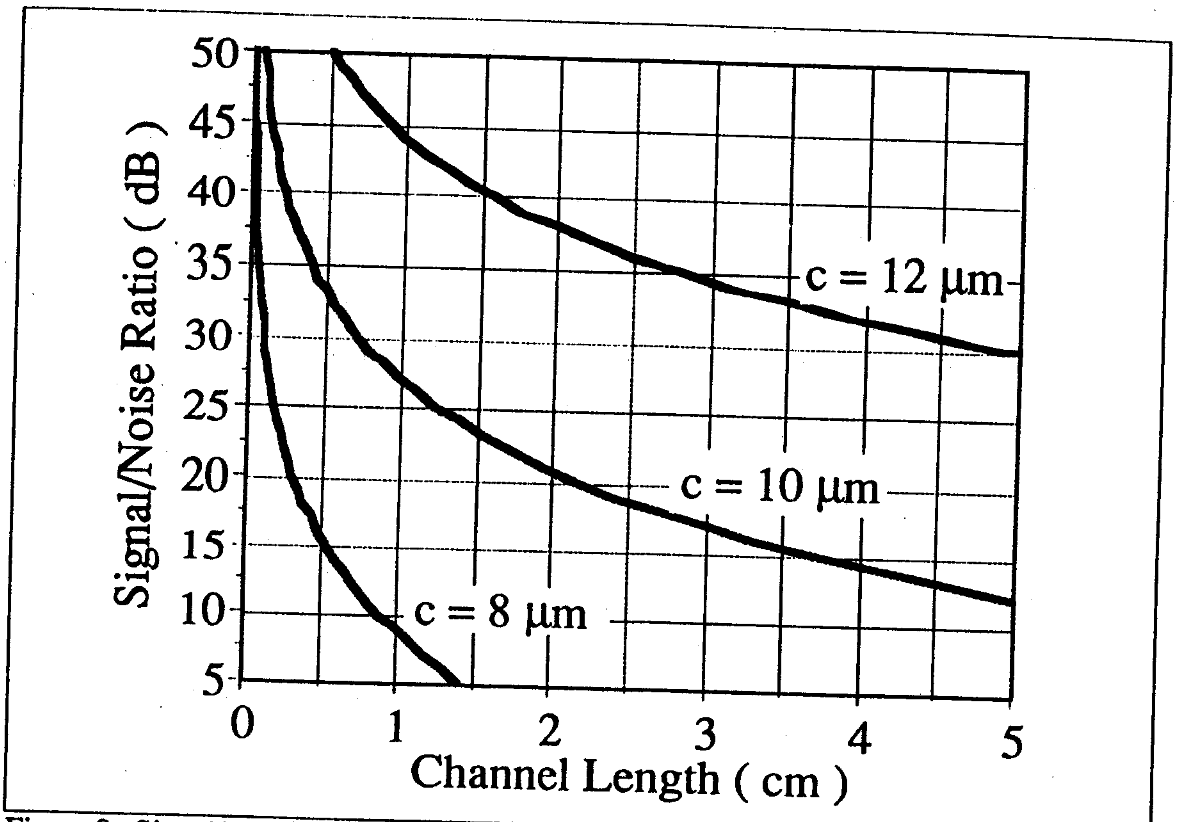

Figure 8. Signal/noise ratio versus maximum channel length with channel separation as a parameter, based on equations (9). $n_1 = 1.5$, $n_2 = 1.0$, $\Delta n = 0.004$, $a = 2$ µm, $c = 8$ µm, 10 µm and 12 µm at $\lambda = 0.6328$ µm were assumed.

## 6. CONCLUDING REMARKS

The minimum channel separation (MCS) and maximum channel length (MCL) of a densely packed SMCWA have been studied using a multiple channel cross-coupling model together with experimental results. Because of the cross-coupling among densely packed channel waveguides, the optical interconnection distance, i.e., channel waveguide length, is not independent of packaging density. The spatial threshold for channel separation depends on the operating wavelength, channel dimensions and the index difference between guiding layer and cladding layers. To obtain a required interconnection distance for a typical polymer based SMCWA, with $n1=1.5$, $n_2=1.0$, and $\Delta n \approx 0.01$ to 0.001, it is necessary to separate the waveguides on the order of several (at least three) channel widths to ensure a desired signal/noise ratio. A large index difference is necessary is to provide high channel packaging density and long interconnection distance at the given signal/noise ratio. A single-mode channel waveguides with dimensions close to the cutoff boundary of the second mode are preferred for high packaging density in an SMCWA design. The maximum packaging density of an SMCWA using coherent light sources is different from those using incoherent light sources due to multiple channel cross-coupling and receiver phase-to-intensity noise conversion. Using a 32 dB required signal/noise ratio criterion for coherent light sources and a 12 dB criterion for incoherent sources, the packaging density ranges from 300-750 channels/cm coherent sources and from 400-950 channels/cm for incoherent sources in a polymer-based SMCWA with a channel length of 2.0 cm, a core index $n_1 =$ 1.5, and a lateral $\Delta n \approx 0.01$ to 0.001. Experimental results are provided to verify the theory presented. The results reported herein provide a useful design tool for a highly parallel optical interconnects using a polymer-based SMCWA.