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# Prism Coupling Measurement of Benzocyclobutene (BCB 4024-40) Polymer for Optical Devices Application

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**Abstract:** Prism coupling method is employed in the characterization process of BenzoCyclobutene (BCB 4024-40) polymer slab structure. This method is used to characterize the polymer refractive index, variation of film thickness with spin coating speed and average value of polymer loss. The information obtained is appreciably useful, particularly in the actual design of optical waveguides and devices based on BCB 4024-40 polymer material.

**Keywords:** BenzoCyclobutene polymer, Fiber scanning technique, Optical waveguides, Prism coupling.

## 1. INTRODUCTION

Integrated optics are having an increasing impact on the development of light wave communication systems with applications such as high speed broadband switching and high speed interconnects for local area network. Undoubtedly, the major performances of integrated optics rely on the waveguiding component. Most optical materials have been widely being used as leading materials for application in optical waveguiding technology due to their certain unique advantages. For example, low-loss and high temperature stability exhibited by silica-on-silicon material [1], wide wavelength range of transparency and large electro-optic (EO) coefficient of LiNbO3 [1] and tunability of material band gap energy over a wide range for the purpose of monolithic optical integration circuit of III-V and II-VI ternary semiconductor compounds [2]. However, the demand in optical networking for photonic components that meet performance criteria as well as economic requirements has opened the door for novel technologies capable of high yield and low cost manufacturing while delivering high performance and enabling unique functions. Of that matter, polymer material has been widely accepted as a new generation material for optical integrated circuit due to its various advantages as compared to others. Such advantages are high performance in terms of low-loss, smaller birefringence, high tunability in terms of large thermo-optic (TO) coefficient, environmentally stable, high yields and low cost [1]].

Optical polymers were engineered in many laboratories worldwide. Classes of polymers used in integrated optics include acrylates, polymides, polycarbonates and olefins (e.g. cyclobutene) [4]. These polymers may then be divided into photosensitive and non photosensitive which differs in fabrication technologies to realize the optical components. Before any waveguide fabrication can be made, material characterization is the first essential process that needs to be done. This process will generate the key parameters that are needed in the device modeling phase, which are material refractive index and material thickness for varied coating speed. Proper modeling and fabrication process can only be realized with proper technique of material characterization.

In this paper, the prism coupling technique is employed in the initial characterization process of BenzoCyclobutene (BCB 4024-40) optical polymer from Dow™ Chemical Co. It is a high purity polymer solution that has been developed for microelectronic applications [5].

## 2. THEORY

Prism coupler was originally demonstrated by Tien et. al. [6] for the purpose to couple light beam into or out from planar structure. The principle of prism coupler is shown in Figure 1, where the coupling prism with refractive index, $n_p$ is located on the asymmetric slab waveguide having a core index of $n_2$, cover index of $n_1$ and substrate index of $n_3$. A single prism can be used to couple many different modes by changing the incidence angle of the optical beam, $\alpha$.

The prism coupling technique utilized the process of measuring the effective index of the propagation mode, which can be obtained by measuring the coupling angle. Consider the air gap between the prism and waveguide is extremely small in Figure 1, the strong light coupling from prism to the guide medium will happen. The phase matching condition is said to happen which state:

$$n_p \sin\theta = n_2 \sin\theta_1 \qquad (1)$$

The right hand side of equation (1) is also known as effective index of the propagation mode. Hence,

$$n_{eff} = n_p \sin\theta \qquad (2)$$

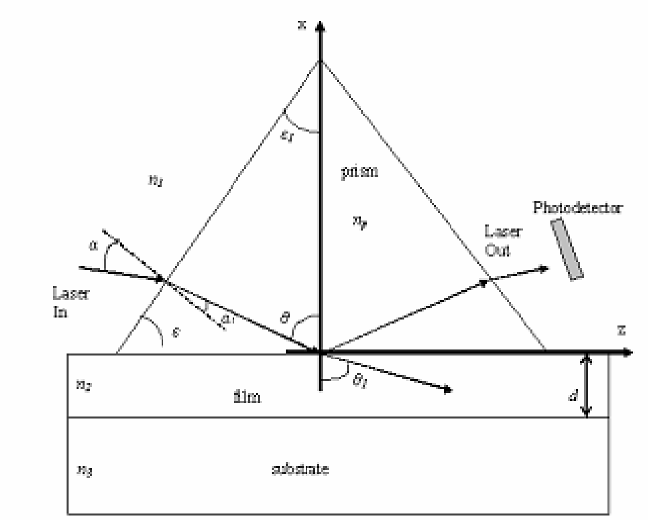


Figure 1. Principle of prism coupler

Application of Snell's Law to the wave propagation in the prism will then elaborate (2) as

$$n_{eff} = n_p \sin\left(\varepsilon + \sin^{-1}\left(\frac{\sin\alpha}{n_p}\right)\right) \qquad (3)$$

Equation (3) clearly shows that effective index can be obtained from measured parameters of coupling angle, $\alpha$; refractive index of prism, $n_p$ and angle of the prism, $\varepsilon$.

The actual value of refractive index and film thickness can be further obtained from the measured effective index value through dispersion equation. For example, consider a transverse electric (TE) propagation, the dispersion equation for three layers asymmetric slab structure can be written as [7]:

$$\tan k_{2x} d = \frac{k_{2x}(\gamma_1 + \gamma_3)}{k_{2x}^2 - \gamma_1\gamma_3} \qquad (4)$$

where;

$k_{2x}$: transverse propagation constant for guiding layer, layer 2 (index $n_2$).

$\gamma_1$ : transverse propagation constant for upper clad layer, layer 1 (index $n_1$)

$\gamma_3$ : transverse propagation constant for lower clad layer, layer 3 (index $n_3$)

$d$ : guide layer thickness

It is shown in [7], that the parameters in (4) can be further elaborated to give:

$$\tan(k_o\sqrt{n_2^2 - n_{eff}^2 d}) = \frac{k_o\sqrt{n_2^2 - n_{eff}^2}\left[\left(k_o\sqrt{n_{eff}^2 - n_1^2}\right)\left(k_o\sqrt{n_{eff}^2 - n_3^2}\right)\right]}{k_o^2\sqrt{n_2^2 - n_{eff}^2} - \left(k_o^2\sqrt{n_{eff}^2 - n_{e1}^2}\right)\left(k_o^2\sqrt{n_{eff}^2 - n_3^2}\right)} \qquad (5)$$

where $k_o$ is the free space propagation constant. From (5), the refractive index value of the guiding layer, $n_2$ can be deduced with known value of effective index and refractive index of other layers for respective wavelength, $\lambda$. However, at least two lowest order modes are needed to propagate inside the guiding layer as two distinct $n_{eff}$ can be obtained which lead to numerical calculation of $n_2$. The guiding layer thickness, $d$ can be further calculated. The same principle works for transverse magnetic (TM) propagation.

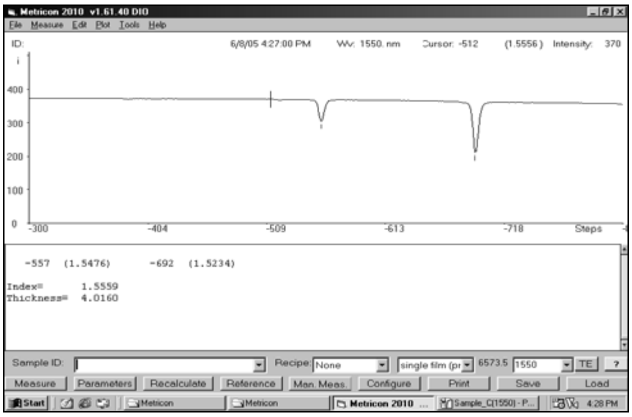
In this work, Metricon™ prism coupler as shown in Figure 2 was employed throughout the characterization process. The coupling laser is set to be at the third optical window of 1550 nm wavelength with both TE and TM polarization, due to the significant advantages of optical device functioning at this wavelength.

Figure 2. Metricon™ prism coupler

## 3. MEASUREMENT RESULTS

The BCB 4024-40 polymer films were prepared according to the fabrication process as described in the following paper [8]. The polymer was evenly coated on the BK-7 glass substrate at different spin speed which is varied from 1000 rotation per minute (rpm) to 6000 rpm. The refractive index of BK-7 glass is 1.50101 at 1550 nm [9]. Two sets of samples were prepared according to the final curing temperature. For soft curing in which the film is more suitable for multilayer application, the curing temperature is 210°C. In case of single layer application, hard curing temperature of 250°C is applied.

The example of graphical output from the single film measurement is shown in Figure 3, which shows the number of coupled modes, material refractive index and film thickness. Two valleys in the figure indicate two distinct propagating modes in the film. The information of material index and film thickness were obtained based on mathematical calculation of equation (5) above. Few samples were prepared according to the curing requirement. In average, it was observed that the refractive index for hard curing samples is 1.5556 and 1.5528 for TE and TM polarization, respectively. For soft curing samples, the average index is 1.5561 and 1.5534 for TE and TM polarization, respectively. From the measurement, it reflects that the number of modes that can be coupled inside the polymer films is heavily depending on the film thickness as described in Figure 4. The relation of film thickness and spin speed is described in Figure 5.



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  -557  (1.5476)      -692  (1.5234)

Index=       1.5559
Thickness=   4.0160
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Figure 3. Graphical output from prisim coupling measurement

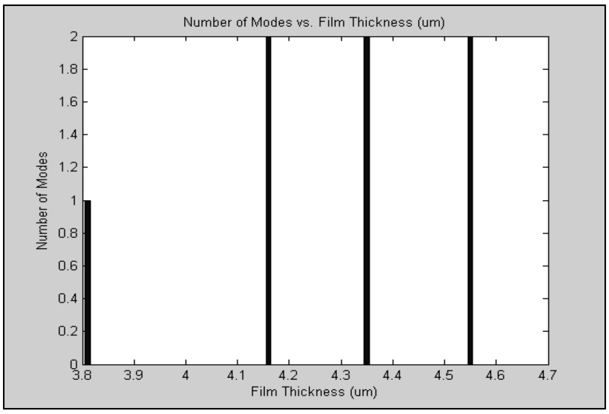


Figure 4. Relation between film thickness and number of modes

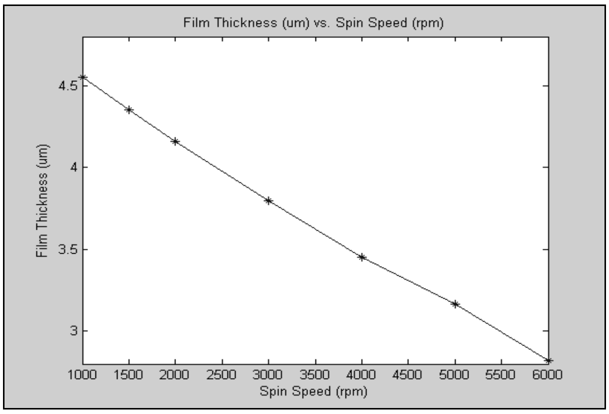


Figure 5. BCB 4024-40 film thickness for various spin coater speed

In the polymer loss measurement, the method of fiber scanning is applied in which an optical fiber is scanned along the film to collect the scattered light which is then read by the photodetector [10]. The schematic diagram of this method is shown in Figure 6 where the air gap between the prism and polymer film is considered small.

The detected power is automatically plotted against the slab distance, which is then used to calculate the polymer loss value, by means of curve fitting method. Note that the loss calculation is done automatically by the prism coupling machine. For brevity, the sample of this measurement is shown in Figure 7. Few samples were measured which gave an average BCB 4024-40 polymer loss value of 1.01 dB/cm.

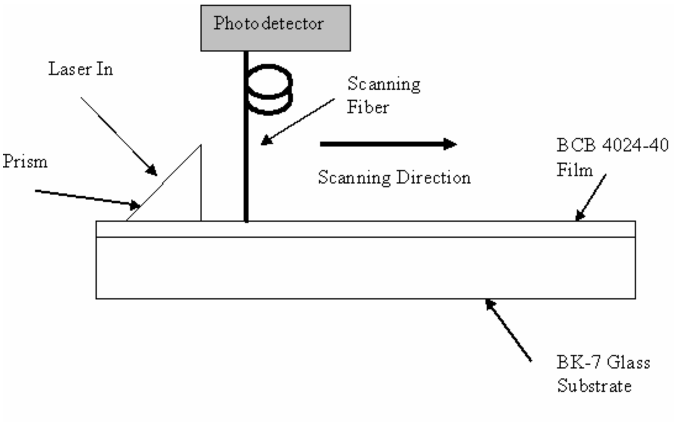
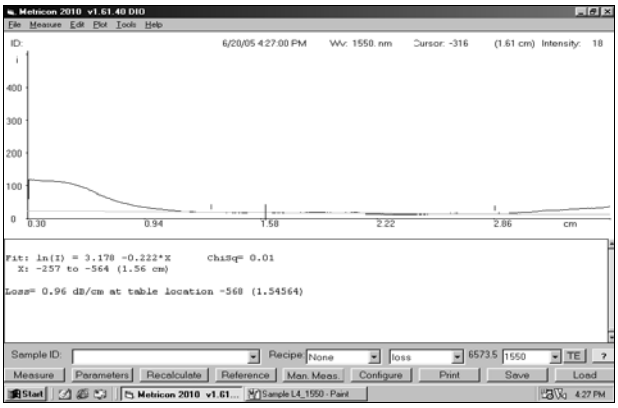


Figure 6. Prism coupling measurement setup of slab loss



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Fit: ln(I) = 3.178 -0.222*X      ChiSq= 0.01
  X: -257 to -564 (1.56 cm)

Loss= 0.96 dB/cm at table location -568 (1.54564)
```

Figure 7. Fiber detected power against slab distance

## 4. DISCUSSIONS

In order to verify for the measured refractive index and film thickness value, the film cutoff parameter is adopted. Cutoff is the minimum condition of a film to guide a particular mode. From manipulation of equation (5) above, the TE cutoff condition for three layers asymmetric structure can be written as:

$$d_{co} > \frac{\lambda}{2\pi\left(\sqrt{\left(n_2^2 - n_3^2\right)}\right)}\left(N\pi + \tan^{-1}\left(\frac{\sqrt{\left(n_3^2 - n_1^2\right)}}{\sqrt{\left(n_2^2 - n_3^2\right)}}\right)\right) \quad (6)$$

where $N = 0, 1, 2, 3, \ldots$ refers to $N^{\text{th}}$ order of confined mode.

Adopting the value of $\lambda$=1550 nm, $n_1$ =1, $n_3$ = 1.50101 and $n_2$ = 1.5556, the cutoff graph of Figure 8 is obtained. From the graph, it shows that the minimum thicknesses that allow the $TE_0$, $TE_1$ and $TE_2$ modes to propagate in BCB 4024-40 film are around 1.1μm, 4.0μm and 6.3μm respectively. This is agreeable to the measured number of modes for different film thickness as described in Figure 4. It shows that for film thickness less than 4.0 μm, only one mode is allowed to propagate. For larger thickness, two modes are allowed. These results provide a high degree of confidence on the measured refractive index and film thicknesses value for varied spin coater speed.

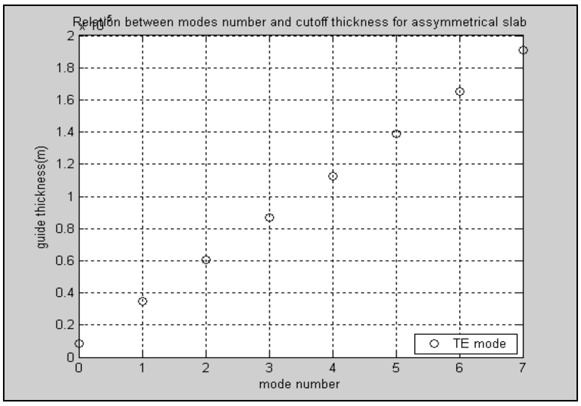

Figure 8. Film cutoff thickness for confined modes

The measured BCB 4024-40 polymer loss value of 1.01 dB/cm is considered small. Although better loss value up to 0.5 dB/cm is recorded for polymeric material [11], the measured loss in this work demonstrate the potential of BCB 4024-40 to be applied in relatively short optical devices application.

## 5. CONCLUSION

A BCB 4024-40 polymer slab film on the BK-7 glass substrate has been characterized for its material refractive index, film thickness for varied coating speed and material loss. It shows that for hard curing process, the index is 1.5556 and 1.5528 for TE and TM polarization, respectively. For soft curing process, the refractive index is 1.5561 and 1.5534 for TE and TM polarization respectively. The film thickness was measured for varied spin coater speed. The results are verified using the cutoff parameter which shows correct number of modes for varied film thickness. The obtained refractive index and film thickness are very useful in the actual development process of photonic devices. The modeling process is critically depending on this characterization results. With the measured material loss equal to 1.01 dB/cm, the BCB 4024-40 polymer is considered to be a good candidate for relatively short optical interconnect application.

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