Feasibility of holographic off-plane waveguide coupler for coupling optical beams to photopolymer waveguide

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ABSTRACT

In this paper, we investigate photopolymer based holographic off-plane coupler experimentally. In our scheme, holograms are recorded inside the photopolymer slab waveguide by two-beam interference. The optical beams are vertically coupled into the waveguide through the recording position over the polymer substrate. The coupled optical beam propagates in the photopolymer slab waveguide. The beam profile radiated from the cut end of the waveguide and measured energy transfer efficiency are presented.

Keywords: off-plane hologram, photopolymer waveguide, integrated photonics

1. INTRODUCTION

Coupling of optical beams to waveguide structure is a critical issue in integrated photonics. Generally coupling configurations can be categorized into two classes, in-plane coupling configuration and off-plane coupling configuration. Figures 1(a) and (b) indicate the in-plane and off-plane coupling configuration, respectively. In the in-plane coupling configuration, an input beam is collimated by using an appropriate coupling optical system and coupled into waveguide through the narrow side cross-section. On the contrary, in the off-plane coupling configuration, the input beam can be vertically incident on the area of grating fabricated on the substrate of the waveguide. The grating coupler diffracts the significant portion of the incident beam to be coupled to the waveguide. The in-plane coupling configuration needs many optical devices such as lens, phase grating, and any other devices. These added devices have increased the complexity of the systems and have needed more effort to align the optics. Whereas, the off-plane coupling configuration just illuminates a plane wave or pre-reserved wave for coupling on surface of waveguide structure. Hence, there are no devices and no effort to align the incident wave to waveguide structure. These features are attractive advantages of the off-plane coupling configuration for integrated photonics. However, in the off-plane coupling configuration, the design of the coupling grating for the off-plane coupling configuration of high efficiency is challengeable and requires active investigations.

Recently, a holography technology for efficient off-plane coupling that is so called OP-CGWH (off-plane computer generated waveguide hologram) was proposed and has been investigated actively. Since OP-CGWH combines the functions of the free-space CGH (computer generated hologram) and IP-CGH (in-plane computer generated hologram), its potential is greater than the free-space CGH and the IP-CGH. It serves as a wavefront transformer between the waveguide and free-space. In the existing OP-CGWH devices, phase holograms of surface relief type on a subwavelength scale are fabricated on AlGaAs or GaAs based waveguides using electron-beam lithography and reactive ion beam etching.

In this paper, we proposed a novel scheme of holographic off-plane waveguide coupler for coupling optical beams to photopolymer waveguide. On the contrary to the existing OP-CGWH using surface relief type hologram, our scheme employees the interferometric holographic technique. In our scheme, holograms are recorded in the slab waveguides made by photopolymer by two-beam interference. In recording, the signal beam is guided through the photopolymer waveguide and the reference beam is vertically illuminated from air to the waveguide structure. In retrieving, the beam matching the Bragg condition is vertically illuminated from air to the waveguide structure and then diffracted beams are...
guided through the photopolymer waveguide. In this paper, we investigate the feasibility of the proposed scheme experimentally.

2. THEORETICAL ASPECT OF OFF-PLANE HOLOGRAPHIC PHOTOPOLYMER WAVEGUIDE COUPLER

In our scheme, the holographic grating is recorded in the photopolymer waveguide. The guided wave in the photopolymer slab waveguide and the vertically incident optical wave from air to the waveguide substrate are taken as the reference beam and the signal beam, respectively. The reference wave i.e. the guided wave of the photopolymer slab waveguide consists of many higher modes of the slab structure. So the three-dimensional interference pattern formed inside the waveguide by the superposition of the reference and the signal waves is quite complicated.

In this section, a feasible analysis method of the somewhat complicated volume hologram formed inside the photopolymer waveguide is addressed. It is plausible to see that the guided reference wave can be represented as the sum of plane wave harmonics with the help of the plane wave expansion method. Based on the plane wave expansion
representation of the reference beam, we can analyze the recording and the retrieving of the off-plane waveguide coupler. Let the reference wave \( E_r(\vec{r},t) \) be expanded by many plane wave components as

\[
E_r(\vec{r},t) = \sum_g E_g e^{i(K_g \vec{r} - \omega t)}
\]  

(1)

where \( \vec{r} \) denotes the position vector. \( K_g \) and \( E_g \) are the wave vector component and the Fourier coefficient. The signal wave is assumed to be a plane wave vertically incident on the substrate of the photopolymer waveguide as

\[
E_s(\vec{r},t) = A e^{i(K_{ow} - \gamma - \omega t)}.
\]

(2)

In recording, the reference wave and the signal wave are superposed at the same position inside the photopolymer waveguide and generate a complicated interference pattern. A volume hologram \( \varepsilon(\vec{r}) \) is built in the photopolymer waveguide as

\[
\varepsilon(\vec{r}) \propto (E_r + E_s)(E_r + E_s)^*(r,t).
\]

(3)

For further investigation, \( \varepsilon(\vec{r}) \) is fully represented as

\[
\varepsilon(\vec{r}) \propto (E_r + E_s)(E_r + E_s)^*(r,t) = (A e^{i(K_{ow} - \gamma - \omega t)} + \sum_g E_g e^{i(K_g \vec{r} - \omega t)})(A e^{i(K_{ow} - \gamma - \omega t)} + \sum_g E_g e^{i(K_g \vec{r} - \omega t)})^*
\]

\[
= \left[ |A|^2 + \sum_g |E_g|^2 e^{i(K_g \vec{r} - \omega t)} \right] - \sum_g |A|^2 - \sum_g |E_g|^2 + \sum_g \left[ |E_g|^2 + |E_g|^2 + A E^* g e^{i(K_{ow} - K_g)\vec{r}} + A^* E_g e^{-(K_{ow} - K_g)\vec{r}} \right]
\]

\[
= \varepsilon_{\text{slow}}(r) + \varepsilon_{\text{fast}}(r).
\]

(4)

As seen in Eq. (4), the volume hologram \( \varepsilon(\vec{r}) \) is the sum of a slowly varying permittivity variation term \( \varepsilon_{\text{slow}}(r) \) and a fast varying permittivity term \( \varepsilon_{\text{fast}}(r) \). \( \varepsilon_{\text{slow}}(r) \) and \( \varepsilon_{\text{fast}}(r) \) indicate respectively

\[
\varepsilon_{\text{slow}}(r) = \left[ |A|^2 + \sum_g |E_g|^2 e^{i(K_g \vec{r} - \omega t)} \right] - \sum_g |A|^2 - \sum_g |E_g|^2
\]

(5)

and

\[
\varepsilon_{\text{fast}}(r) = \sum_g \left[ |A|^2 + |E_g|^2 + A E^* g e^{i(K_{ow} - K_g)\vec{r}} + A^* E_g e^{-(K_{ow} - K_g)\vec{r}} \right] = \sum_g \varepsilon_g(r).
\]

(6)

In the above analysis, it is assumed that the intensity profile of the reference wave \( |E_r(\vec{r},t)|^2 \) is a slowly varying function of \( r \). The fast term \( \varepsilon_{\text{fast}}(r) \) is the superposition of many elementary holograms that are viewed as holograms formed by the signal wave \( E_s(\vec{r},t) \) and an individual spectra component of the reference wave \( E_g e^{i(K_g \vec{r} - \omega t)} \) since the elementary hologram takes the representation of
\[ \varepsilon_g(r) = |A|^2 + |E_g|^2 + AE_g^* e^{i(K_{wv} - K_g)v} + AE_g e^{-i(K_{wv} - K_g)v}. \] (7)

Therefore if the effect of the slowly varying term in ignored, we can approximately calculate the diffraction efficiency of the volume hologram formed inside the photopolymer waveguide by separately calculating the diffraction efficiency \( \eta_g \) of each elementary hologram \( \varepsilon_g \). The well-known Born approximation method is feasible for the calculation of diffraction efficiency of an elementary hologram.

On the other hand, in retrieving process, the fine alignment of the incident beam is important for obtaining high coupling efficiency. Figure 2 shows the phase-matching diagram of an elementary hologram \( \varepsilon_g \). It is assumed that the elementary hologram has a periodic profile with period \( \Lambda \). In Fig. 3 the above region of horizontal line indicates the wave number of reflected region and the below region indicates the transmission region. The wave number \( k_{zm} \) (air space) and \( k'_{zm} \) (waveguide space) of horizontal region are the same because of the boundary condition. Their corresponding vertical wave number was obtained from the dispersion relation. In the waveguide region, the wave number is

\[ k'_{zm} = \hat{x}k'_{xm} + 2k_{zm} \]
\[ k'_{zm} = k_{zm} = k_{z0} + m \frac{2\pi}{\Lambda} \]
\[ k'_{xm} = \sqrt{\omega^2 \mu_1 \varepsilon_0 - k_{zm}^2} \] (8)

![K-diagram analysis for the inner coupling](image)

Figure 2. K-diagram analysis for the inner coupling
Here we consider the case in which the diffraction order $m$ is $+2$. In this order, the horizontal wave number $k_{x2}$ is bigger than the wave number $|k|$. From the dispersion relation, the vertical wave number $k_{z2}$ is purely imaginary. So it decays away from the surface. In the transmission region (wave guide region), the vertical wave number becomes a real number by the equation.

An elementary hologram $E_g$ can play a role of an input or output coupler as shown in Fig. 3. For this, the incident angle $\theta_i$ must satisfy the following phase matching condition for grating period $\Lambda$

$$k_{z0}n_0 \sin \theta_i + m \frac{2\pi}{\Lambda} = \beta$$  \hspace{1cm} (9)

Conclusively, we can see that the diffraction efficiency and phase matching condition of the volume hologram formed inside the photopolymer can be analyzed by separately considering each elementary hologram $E_g(r)$ of Eq. (7) ignoring the slowly varying permittivity term in Eq. (5).

![Diagram](image_url)

**Figure 3. The phase-matching condition of coupler**

### 3. EXPERIMENT AND RESULTS

Figure 4 shows the recording setup of the off-plane holographic coupler. We used the Nd:YAG laser with the wavelength of 532 nm for recording the off-plane holographic coupler. The beam splitter is used to generate reference
and signal beams. The reference beam through the coupling lens is coupled into the photopolymer waveguide. The photopolymer film is used as the waveguide slab. The depth of the waveguide is 38 $\mu$m. The signal beam expanded by the beam expander illuminates the surface of the photopolymer waveguide. The interference pattern of reference and signal forms a volume hologram inside the photopolymer waveguide. This hologram plays a role of a grating coupler. It was noted that the reference beam was widely dispersed in the waveguide because of the slab structure. In practice, since the intensity profile of the reference wave inside the waveguide is not uniform, the magnitude distribution of the permittivity variation of the holographic grating is not uniform. Hence the measured diffraction efficiency of the holographic coupler varies with the incidence position of the input beam. In the experiment, through several trials, the incidence position is searched on the substrate of the waveguide for obtaining the maximum diffraction efficiency.

Figure 5 shows the far-field pattern of the output wave radiated from the side facet of the photo-polymer waveguide and the retrieving schematic. A Nd:YAG laser with wavelength of 532 nm was used for retrieving the image. The image of the output wave was taken from the CCD camera. The size of the image is $0.3 \times 0.25$ cm and the diffraction efficiency is about 17%. This diffraction efficiency is measured at the position where the diffraction efficiency becomes the highest value.

As seen in the far-field pattern of Fig. 5, two separated patterns are manifested. This phenomenon may be induced by the structure of the holographic coupler. Since the photopolymers are very flexible, a fixing body is needed for fixing the photopolymer film. We fixed the photopolymer film between two glass plates tightly to make the waveguide. However the side facet of the waveguide was not well polished and perfectly attached. Since the index of the glass plate is similar to that of the photopolymer, propagating wave is coupled to the glass plates. Thus the guided wave is separately coupled into two glass plates. In other words, a portion of guided wave is divided into two regions of the photopolymer waveguide.

![Figure 4. Recording setup of the off-plane holographic coupler](image-url)
5. CONCLUSION

In this paper, a generic theory of photopolymer based grating couplers was explained based on the slowly varying approximation for the scalar analysis of volume holograms and simple phase matching analysis. The fabrication scheme of the off-plane holographic coupler is presented and experimentally demonstrated. An off-plane holographic coupler can be easily recorded on the photopolymer waveguide by the holographic interference method. This coupler can couple the wave in free-space to the waveguide structure. This regime has many advantages such as facility of coupling, cheaper and easy fabrication, small size, and high solubility compare with the conventional coupler. In the proposed scheme, considerably high diffraction efficiency (~17%) was obtained. If we manipulate the signal by using other optical devices, it is expected that the multiple functional elements can be realized by multiplexing method such as guided beam shaping, or focusing.

REFERENCES

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REFERENCES