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A Pseudo-Self-Imaging Phenomenon in Multimode Waveguides

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This study introduces an undefined self-imaging phenomenon, called here the pseudo-self-imaging phenomenon. The relative phases of the guided modes were used to discover how the pseudo-self-images are formed. The pseudo-self-image was found and measured experimentally. The experimental results showed that both the pseudo-self-image and the 0-dB self-image have similar intensity values and have opposite positions in the lateral direction.

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I. INTRODUCTION

Multimode interference (MMI) couplers based on a self-imaging phenomenon have been experimentally shown to exhibit several superior characteristics, including large fabrication tolerance, low polarization dependency, and low wavelength dependency [1]. For these reasons, MMI couplers are used more often than directional couplers for practical applications [2]. The wavelength filters that combine/separate wavelengths are one of many MMI coupler applications [3]. Such wavelength filters are designed to match the self-image forming length of each wavelength. This is why the device length must become extremely long and why propagation loss must be considered. These characteristics become critical disadvantages when dealing with very low-intensity optical signals.

A previous work that aimed to reduce the length of the multimode waveguide suggested a novel imaging phenomenon [4]. This imaging phenomenon can not be explained by general MMI theory. However, the work did not show why the images appear. The previous work stated that the image forming length is 5-times less than the generally known self-imaging length [4]. However the 5-times reduction in the self-imaging length is not always acceptable and rather depends on various physical factors such as the width, the thickness, and the index difference.

This paper analyzes the undefined self-imaging phenomenon (called the pseudo-self-imaging phenomenon here and shown in Fig. 1) and demonstrates the reason for its appearance. First, a two-fold (3-dB) self-image and a single (0-dB) self-image are analyzed by using the phase relations of each guided-mode. Second, the pseudo-self-image is analyzed by the same method and its existence is proved experimentally.

II. SELF-IMAGES AND PHASE RELATIONS OF GUIDED-MODES

There are several guided-modes in a multimode waveguide, and the self-image is formed by the interference of these guided-modes. The self-image can be estimated from the phase relations of the guided-modes. However,

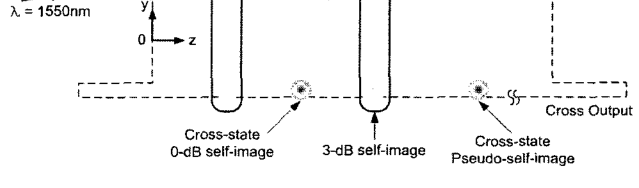


FIG. 1. Schematic of the self-images and the pseudo-self-images in a multimode waveguide with a general interference effect.

in MMI theory, the propagation constants of each guided-mode are defined under a perfectly confined condition. Because of the effects of the Goos-Hänchen shift [5], there are large phase differences for each guided-mode between the theoretical predictions and the actual phenomena [1,6].

To analyze the phase differences, the propagation constants of each guided-mode are found through guided-mode analysis (GMA) [7], and the phases of the guided-modes are solved by eq. (1) and mode propagation analysis (MPA) [1]:

$$\phi_\nu(z) = \exp[j(\beta_0 - \beta_\nu)z] \tag{1}$$

where ν is the mode number, β_0 is the propagation constant of the fundamental mode and β_ν is the propagation constant of each guided-mode.

In addition, in order to determine the image forming lengths for each self-image, the overlap integral is computed by applying the optical fields ($\Psi(y,z)$) at each propagation step and the fundamental mode profile ($\Psi_{0\_out}(y)$) for the access waveguide. From that, the excitation coefficient is defined as $c_\nu(z)=\{\int \Psi(y,z)\cdot \Psi_{0\_out}(y)dy\}/\{\int \Psi^2_{0\_out}(y)dy\}$.

The theoretical phase relations needed for each guided-mode to form 0-dB and 3-dB self-images are shown in eq. (2) [1].

$$\phi_\nu(z) = \begin{cases} (1)_{\nu=even}(-1)^p_{\nu=odd} & \text{for } 3-dB\ self-images \\ 1 & \text{for } 0-dB(bar-state)\ self-images \\ (-1)^\nu & \text{for } 0-dB(cross-state)\ self-images \end{cases} \tag{2}$$

where p is the image-forming period and is restricted to only odd numbers. Each self-image can be formed when the relative phases of the even-order modes and odd-order modes are satisfied as in eq. (2).

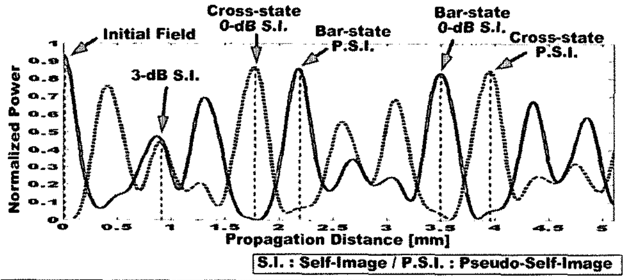
The simulation model is the MMI coupler with a buried-type silica-based optical waveguide structure (index difference (Δ) = 0.75%, clad index = 1.4583, core index = 1.4693, access waveguide width = 6 μm). The MMI coupler with the general interference effect has a width (W_{MMI}) of 18 mm and a thickness (T_{MMI}) of 6 mm, and the total simulation length (L_{MMI}) of the MMI coupler is $9L_\pi$ where $L_\pi = \pi/(\beta_0 - \beta_1)$.

The information from the simulation results of each guided-mode is shown in Table 1. The positions of the formed self-images are found from Fig. 2 (a), which is solved by the excitation coefficient. After that, the phases of the even- and the odd-order modes at the distances of the formed self-images are calculated by eq. (1) and compared with the relations in eq. (2). Fig. 2 (b) shows the relative phases for the even- and the odd-order modes in the complex planes. Also, the length of each arrow is shown as the vector sum of the excitation coefficients for each guided-mode.

To form the 3-dB images in eq. (2), the even-order mode should have the same phase as the fundamental mode, and the odd-order mode should have a phase difference of -90° with respect to the fundamental mode. However, both the even- and the odd-order modes have an offset of +8° from the theoretical case in Fig. 2 (b). For the cross-state 0-dB self-image, the even-order mode has an offset of +9° and the odd-order mode has an offset of +8° from the theoretical cases in eq. (2). From these results, it is clear that all the offset states are positive. This condition can be explained using the effective widths of each guided-mode and the image forming conditions in eq. (2). Because the higher order mode has a larger effective width and larger lateral wavenumber, the higher order mode has a larger accu-

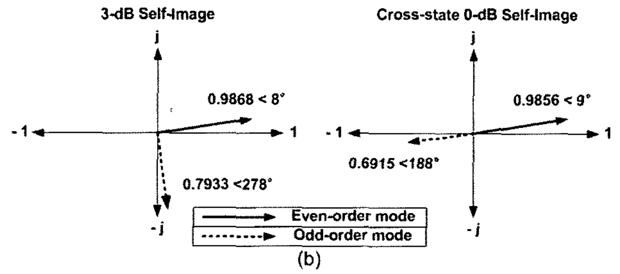
TABLE 1. Information on each guided-mode for the simulation model.

Mode Number	Propagation Constant	Excitation Coefficient
Fundamental Mode	5.94358×10^6	0.3297
1st-order Mode	5.9381×10^6	0.4676
2nd-order Mode	5.92922×10^6	0.1823
3rd-order Mode	5.91776×10^6	0.0060



Self-Image	Distance [μm]	Excess Loss [dB]	
		Bar Output	Cross Output
Initial Field	0	-0.329	-35.075
3-dB S.I.	898.86	-3.342	-3.538
Cross-state 0-dB S.I.	1769.09	-24.686	-0.613
Bar-state P.S.I.	2175.58	-0.662	-11.943
Bar-state 0-dB S.I.	3492.38	-0.795	-14.123
Cross-state P.S.I.	3950.40	-13.292	-0.732

(a)



(b)

FIG. 2. Simulation results for the self-images in the multimode waveguide with a width of 18 μm and a thickness of 6 μm. (a) The results of the overlap integral and the data table for the self-images. (b) The phase relations between the even- and odd-order modes for the 3-dB self-image and the 0-dB self-image.

mulated phase-mismatch [1,7]. Moreover, the higher order mode could have a longer optimized length with the required relative phase for each self-image. For this reason, the phase of the lower order mode with the larger excitation coefficient has to be passed through the required relative phase and the optimized image forming length to form a self-image. Accordingly, the required phase relation between the even- and odd-order modes for the image forming condition could occur with positive phase offset values. In addition, the guided-modes have their own effective widths, and the effective widths of each guided-mode are associated with the Goos-Hänchen shift at the ridge boundaries [1,6,7]. Moreover, the term of the effective width is included in the beat length (L_π) and in the phase term of the propagating field's distribution [1]. For this reason, the phase mismatches could be caused by the Goos-Hänchen shift effect.

In Fig. 2 (b), the even- and odd-order modes' amplitudes are different for both the 3-dB self-image and the 0-dB self-image. For this reason, the intensities of both images are smaller than those of the initial field. In addition, it would be possible to find more optimal self-image lengths of a MMI coupler and a correspondingly more efficient device through perturbation of the phasor diagrams in Fig. 2 by varying the thickness or width of the MMI coupler.

III. PSEUDO-SELF-IMAGING PHENOMENON

Because the relative phases of the guided-modes are not the same as the theoretical ones in a multimode waveguide, it is possible that an undefined self-image can be produced. In this paper, such a phenomenon is called the 'pseudo-self-imaging phenomenon'. This phenomenon can be observed in Fig. 2 (a), which shows the bar-state pseudo-self-image at a distance of 406.49 mm beyond the cross-state 0-dB self-image. It is formed opposite from the cross-state 0-dB self-image for the lateral direction. In other words, the bar-state pseudo-self-image forms at the same position as the input position in the lateral direction. Because of its position in the lateral direction, the guided modes should be in the same phase state as the input field for the pseudo-self-image. Similarly, the cross-state pseudo-self-image is formed at a distance of 458.02 μm beyond the bar-state 0-dB self-image. In order to understand the reasons for the formation of the bar-state pseudo-self-image, the relative phases of the guided-modes and the relative phases of the even- and odd-order modes have been confirmed at the distance of the bar-state pseudo-self-imaging, as shown in Fig. 3.

The relative phase variations of the guided-modes along the propagation distance are shown in Fig. 3 (a), and the phase states of the guided-modes at the optimized distance for the bar-state pseudo-self-image are shown in Fig. 3 (b) and (c). The graph of the relative phase variation can be solved using the phase factor in eq. (1) and the sine function. By considering the relations in eq. (2), it can be shown in Fig. 3 (a) that the phase-matched distances for the odd- and even-order modes are 2161.27 μm and 2187.03 μm, respectively. Moreover, the optimized distance for the bar-state pseudo-self-image is 2175.58 μm which is almost the halfway point between the phase-matched distances for both the even- and the odd-order modes. Fig. 3 (a) also shows that the relative phases of all the guided-modes converge to 0° for the bar-state pseudo-self-image. However, as shown in Fig. 3 (b), the relative phase differences of the second- and third-order modes more closely approach 0° than the first-order mode. Because the relative phase of the first-order mode - which has the largest excitation coefficient - has the largest phase error from the theoretical, it could be estimated that a side-lobe exists with the bar-state pseudo-self-image.

When comparing the pseudo-self-images with the 0-dB self-images in Fig. 2 (a), it can be seen that both fields have almost the same intensities as that at the opposite position on the y-axis. Also, from the table in Fig. 2 (a), the excess losses for the cross-state and the bar-state 0-dB self-images are -0.613 dB and -0.795 dB, respectively. For the bar-state and the cross-state pseudo-self-images, the excess losses are -0.662 dB and -0.732 dB, respectively. For the bar-state pseudo-self-image, the phase error of the first-order mode is the largest, so the bar-state pseudo-self-image may have a lower extinction ratio than does the cross-state 0-dB self-image. However, the cross-state pseudo-self-image has slightly

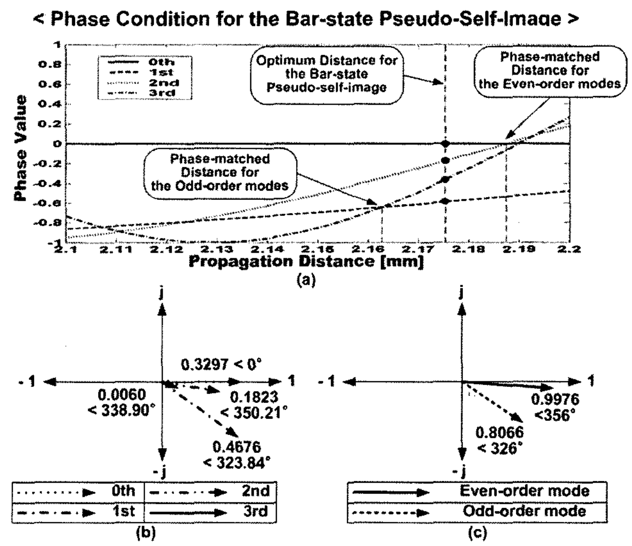


FIG. 3. The phase relations for the pseudo-self-image. (a) The relative phase variations of the guided-modes along the propagation distance. (b) The phase relations between each guided-mode. (c) The phase relations between the even- and odd-order modes.

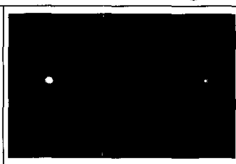
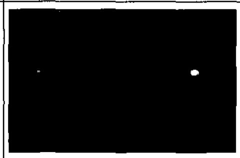
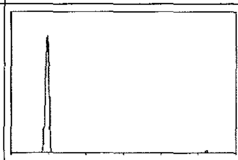
better excess loss and a similar extinction ratio when compared with the cross-state 0-dB self-image. These results could be caused by the accumulation of phase-mismatch. The characteristics of the pseudo-self-image will be discussed as follows along with the experimental results.

IV. EXPERIMENTAL CONFIRMATION FOR PSEUDO-SELF-IMAGE

Until now, the discussion of pseudo-self-images was based on simulation results. From the forward results, in order to experimentally prove the existence of the pseudo-self-images, a multimode waveguide with W_{MMI}=18 μm and T_{MMI}=6 μm was measured with a light source whose wavelength is 1550 nm. To measure more practical results, as shown in Fig. 1, the bar- and the cross-output waveguides are formed at the end of the multimode waveguide for coupling the output field to single-mode fibers. Moreover, the excess loss and the extinction ratio of the pseudo-self-image are measured and compared with those of the 0-dB self-image. The excess loss is defined as -10 log (I_{out}/I_{single}) [dB], where I_{single} is the output intensity of the single-mode waveguide with the same length as the measured multimode waveguide, including the in/output waveguides, and I_{out} is the output intensity of each output waveguide. The extinction ratio is defined as -10 log (I_{min}/I_{max}) [dB], where I_{max} is the larger output intensity for both the bar- and cross-output waveguides and Imin is the smaller output intensity.

The experimental results for both the 0-dB self-image and the pseudo-self-image are shown in Table 2. The field profiles and the intensity profiles are measured using an infrared camera, and other items in Table 2 are measured by the fiber-coupling method. Both the self-images have opposite positions from each other in the lateral direction. The intensity profiles for both the self-images are almost the same. The excess loss has been measured, and the results are -0.1 dB and -0.3 dB for the 0-dB self-image and the pseudo-self-image, respectively. These results could have occurred because of the phase errors of the guided-modes. It can be expected that the pseudo-self-image can have similar or larger values of intensity than the 0-dB self-image. The extinction ratios are also measured, and the results are -21.65 dB for the 0-dB self-image and -18.33 dB for the pseudo-self-image. From these results, it can be proved that the pseudo-self-images have relatively large values of extinction ratios, as predicted from the simulation results. Finally, the distance difference between the 0-dB self-image and the pseudo-self-image is measured. From the result, it can be shown that the pseudo-self-image is formed after the 0-dB self-image and the distance difference is 360 μm, as shown in Table 2. In

TABLE 2. Experimental results for the 0-dB self-image and the pseudo-self-image in a multimode waveguide with a width of 18 μm and a thickness of 6 μm.

	0-dB Self-Image	Pseudo-Self-Image
Field Profile		
Intensity Profile		
Excess Loss	-0.1 dB	-0.3 dB
Extinction Ratio	-21.65 dB	-18.33 dB
Distance Difference	360 μm	

MMI theory, no two self-images have an approximate distance of 360 μm between them in a multimode waveguide with Δ=0.75% and W_{MMI}=18 μm.

From all of these results, the existence of the pseudo-self-imaging phenomenon is proven, as are associated characteristics including intensity, excess loss, extinction ratio, and lateral and longitudinal positions. Also, the results for the intensities and the imaging distance difference of both the self-images show that this phenomenon is not mentioned in the generally known multimode interference theory.

V. CONCLUSION

This paper explored the cause and characteristics of the pseudo-self-imaging phenomenon by analytic methods such as GMA, and MPA, and proved the existence of the pseudo-self-image through experimental results. From the simulation results, it can be confirmed that the pseudo-self-image can be produced by natural interference between each guided mode, rather than any artificial work. Also, the pseudo-self-images' intensity, extinction ratio, and position have been experimentally measured. From the experimental results, its intensity is only 0.2 dB less than the 0-dB self-image and it may be confirmed that the pseudo-self-image could have a relatively high extinction ratio. Moreover, the results show that the pseudo-self-image would be in a totally opposite position in the lateral direction and would be 360 μm-farther away in the longitudinal direction when compared with the 0-dB self-image.

Ultimately, the possibility for the formation of a pseudo-self-image would exist in any multimode waveguide, and the relative intensities of the pseudo-self-images may be almost the same as the ones for the 0-dB self-images. This phenomenon can be applied to optical devices that filter two or more different wavelengths in a single device for both reducing the device lengths and increasing the device reliability.

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