Fiber-optic modal coupler using periodic microbending

J. N. Blake, B. Y. Kim, and H. J. Shaw

Edward L. Ginzton Laboratory, W. W. Hansen Laboratories of Physics, Stanford University, Stanford, California 94305

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An efficient LP_{01} to LP_{11} modal coupler using periodic microbends, spaced by a beat length between the modes, was built and tested. The optical-wavelength dependence of the device is investigated, as are the polarization characteristics and the LP mode approximation. Finally, the loss of the modal coupler was measured as a function of wavelength.

Periodic coupling between the various modes in an optical fiber is of current interest in interferometric and sensor applications. Coupling between the two cross-polarized modes of a single-mode birefringent fiber has been studied, as has coupling between the LP_{01} and LP_{11} modes in a circularly symmetric fiber. The latter case was achieved by periodically squeezing the fiber. It has been demonstrated in theory, however, that coupling between the LP_{01} and LP_{11} modes can be achieved much more efficiently by introducing microbends into the fiber instead of squeezing it. This Letter describes such an efficient LP_{01} to LP_{11} modal coupler that was built and tested. Microbends were introduced into the fiber, spaced by a beat length between the two modes. The optical-frequency dependence of the modal coupler is investigated. The polarization characteristics and the LP mode approximation both inside and outside the coupling region are discussed. Finally the insertion loss of the modal coupler was measured.

The length of fiber over which the relative phase delay between the LP_{01} and LP_{11} modes is 2\pi (L_B) is

\[ L_B = 2\pi / \Delta \beta, \]

(1)

where \( \Delta \beta \) is the difference in the propagation constants of the two modes along the fiber. \( L_B \) can be determined by solving the characteristic equations for the two modes to find the \( \beta \)'s. For a step-index fiber with core radius \( a \), core and cladding refractive indices \( n_c \) and \( n_{cl} \), respectively, and assuming that the modes are weakly guided, \( L_B \) can be written in the following form:

\[ L_B = 2\pi a \left( \frac{Z}{\Delta} \right)^{1/2} \cdot f(V), \]

(2)

where

\[ \Delta = \frac{(n_c - n_{cl})}{n_c} \approx \frac{(n_c - n_{cl})}{n_{cl}} \]

(3)

and \( V \) is the normalized frequency. \( f(V) \) depends only on the normalized frequency and is plotted in Fig. 1. It is interesting to note that \( f(V) \) has a minimum of 0.704 at \( V = 3.03 \). Near this frequency \( L_B \) is insensitive to changes in \( V \). This is equivalent to the fact that at this frequency the two modes have the same group velocity. (See, for example, Ref. 4.)

An idealized model for the periodic microbend structure is to consider the fiber as having \( n \) discrete, identical, equally spaced coupling points. Loss is neglected in the following analysis. Let \( u_i \) be the field of the LP_{01} mode after the \( i \)th coupling point and \( v_i \) be the field of the LP_{11} mode after the \( i \)th coupling point. Then, taking the coupling coefficient of each coupling point to be \( K \) and the relative phase delay between the two modes at successive coupling points to be \( \theta \), the total field after the \( i \)th coupling point can be expressed as

\[ \begin{bmatrix} u_i \\ v_i \end{bmatrix} = \begin{bmatrix} \sqrt{1 - K^2} & jK \\ jKe^{j\theta} & \sqrt{1 - K^2}e^{j\theta} \end{bmatrix} \begin{bmatrix} u_{i-1} \\ v_{i-1} \end{bmatrix}. \]

(4)

Thus, after \( n \) coupling points,

\[ \begin{bmatrix} u_n \\ v_n \end{bmatrix} = \begin{bmatrix} \sqrt{1 - K^2} & jK \\ jKe^{j\theta} & \sqrt{1 - K^2}e^{j\theta} \end{bmatrix}^n \begin{bmatrix} u_0 \\ v_0 \end{bmatrix}. \]

(5)

Taking \( u_0 = 1 \) and \( v_0 = 0 \), i.e., only the LP_{01} mode enters the coupling structure,

\[ |v_n|^2 = K^2 \sin^2(n \sin^{-1} Z), \]

(6)

where

\[ Z = \left( K^2 \cos^2 \frac{\theta}{2} + \sin^2 \frac{\theta}{2} \right)^{1/2}. \]

(7)

For a structure with the coupling points spaced such that there is perfect phase matching (\( \theta = 0 \)), this expression reduces to the familiar

\[ |v_n|^2 = \sin^2(n \sin^{-1} K). \]

(8)

Since \( L_B \) is relatively insensitive to changes in frequency over a wide bandwidth, \( K \) will also remain relatively constant in that frequency range. Thus it can be seen from Eqs. (6) and (7) that the power coupled between the modes will not vary much with changes in frequency. Thus a modal coupler using periodic microbends will be a broadband device. In order to achieve significant filtering action, \( n \) would have to be quite large, making the interaction region long.
An LP\textsubscript{01} to LP\textsubscript{11} mode coupler was built and tested. The microbends were achieved by wrapping two cylinders with 0.025-cm copper wire (approximately \(L_B\) for the fiber that was used) and bending the fiber between these two ridge structures. (See Fig. 2.) The spacing between the microbends could be accurately controlled by angling the fiber by a small amount with respect to the wires. To ensure that all the wires were squeezing the fiber with approximately the same pressure, one of the cylinders had a flat milled on it so that one set of wires could slightly readjust its positions so that equal pressure was exerted on all the points of contact with the fiber. The device that was built had 13 wire wraps. The fiber that was used had a core radius of 2.28 \(\mu\)m and a cutoff wavelength for the second mode of 671 nm. Also needed in the testing was an LP\textsubscript{11} mode stripper. This was achieved by wrapping the fiber around a 0.64-cm post with at least 15 wraps.

Figure 3(a) shows the experimental setup used in testing the coupling efficiency and in determining the beat length. The first LP\textsubscript{11} mode stripper ensured that only the LP\textsubscript{01} mode entered the coupling region. The fiber angle was adjusted within the coupling region, and the amount of bending was adjusted to maximize the coupling to the LP\textsubscript{11} mode. The second mode stripper then dissipated this energy, leaving only the light in the uncoupled or overcoupled LP\textsubscript{01} mode to reach the detector. After accounting for the insertion loss of the device, the maximum coupling to the LP\textsubscript{11} mode achieved was 99.68\%. In order to achieve this maximum coupling, the fiber was bent under a load of 250 g. This compares with 3 kg of loading used in the previously reported squeezing device."\textsuperscript{2}\) Overcoupling was also easily achieved by bending the fiber more. By measuring the angle at which the fiber was laid across the wires, the beat length was calculated. The measured beat lengths were 270 and 265 \(\mu\)m at \(\lambda = 590\) and \(\lambda = 496.5\) nm, respectively. These compare with theoretical values of 264 and 262 \(\mu\)m. The results were well within the accuracy of the measurements and the fiber parameter data.

These results show that the beat length over this wide-frequency band is almost constant, in good agreement with the theory. That the coupling was indeed approximately constant was checked by scanning the frequency of a dye laser from 580 to 610 nm while coupling approximately 100\% of the power from the first mode to the second mode. The power left in the first mode was observed to remain less than 20 dB below the situation with no bending for constant bending of the fiber over this frequency range.

The second-order mode in a step-index fiber consists of four almost degenerate modes: TE\textsubscript{01}, TM\textsubscript{01}, and the two polarizations of HE\textsubscript{21}. In the LP approximation, hybrids of these modes are formed to give the four LP\textsubscript{11} modes. It should be noted that as a single LP\textsubscript{11} mode propagates down the fiber, it will not remain as purely that LP\textsubscript{11} mode, because of the slight nondegeneracies of the true eigenmodes. Over a length of fiber small compared with the beat lengths of the true eigenmodes, however, the LP approximation will remain valid. This constraint is certainly met for a periodic microbending structure, since it would typically be of the order of 1 cm or less in length. Because some birefringence is introduced by the microbends,\textsuperscript{3} the eigenpolarization states of all the modes, both LP\textsubscript{01} and LP\textsubscript{11}, should be taken as parallel to or perpendicular to the plane of the microbends. As an aside, it should be noted that if this device were to be constructed with highly birefringent fiber, it would be necessary to align one of the birefringent axes with the plane of the microbends in order to preserve the simple eigenstates of all the modes.

Taking the microbends all to be in one plane, and

![Fig. 1. Dependence of the normalized beat length between the two lowest-order modes in a step-index fiber on the normalized frequency.](image)

![Fig. 2. Fiber subject to periodic microbending.](image)

![Fig. 3. (a) Experimental setup for measuring the beat length between the LP\textsubscript{01} and LP\textsubscript{11} modes and for determining the coupling efficiency between the two modes. (b) Experimental setup for viewing the polarization and mode properties of the modal coupler. DMF, double-moded fiber; MS, LP\textsubscript{11} mode stripper; MC, modal coupler; PC, polarization controller.](image)
the $LP_{11}$ modes to be the second-order eigenmodes of the system, the symmetry properties of the structure will allow only one of the $LP_{11}$ modes to be generated from each eigenpolarization of the $LP_{01}$ mode. The reasons for this are that the polarization of the wave is preserved in the coupling process and that the symmetry of the fiber is preserved in the plane perpendicular to the plane of microbending. Since the $LP_{01}$ mode field distribution is symmetric about the fiber axis, and the $LP_{11}$ mode field distribution is antisymmetric in one plane about the fiber axis, the overlap integral between the two modes will be nonzero only in the plane where the symmetry of the fiber is broken. The $LP_{11}$ modes that are generated in the coupling process are shown in Fig. 4.

The experimental setup for determining the polarization and mode properties of the modal coupler is shown in Fig. 3(b). Here any desired polarization state of the $LP_{01}$ mode can be injected into the modal coupler. As was expected, only the $LP_{11}$ mode with the proper spatial symmetry was seen on the screen, regardless of the input polarization state of the $LP_{01}$ mode. Also, the linear polarization states parallel and perpendicular to the plane of the ridges were maintained in the coupling process. A short fiber length at the output of the coupler was needed to ensure that the $LP_{11}$ mode did not change its nature as a result of the slight nondegeneracies of that mode.

Figure 5 shows the losses to the radiation modes for the 13-ridge coupler. The measurements were all taken for coupling strengths that gave almost 100% mode conversion. As can be seen, the losses become high near the second mode cutoff, possibly limiting applications in that region.

In conclusion, we have demonstrated an efficient $LP_{01}$ to $LP_{11}$ modal coupler. With just a 13-ridge device, the light could be overcoupled between the modes several times before the fiber broke. The device is broadband, as predicted by the theory. The polarization-holding characteristics, as well as the $LP_{11}$ mode patterns generated, were also consistent with the predictions. Finally, the loss was measured and it was found that the losses rapidly increase as the second mode cutoff is approached.

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References