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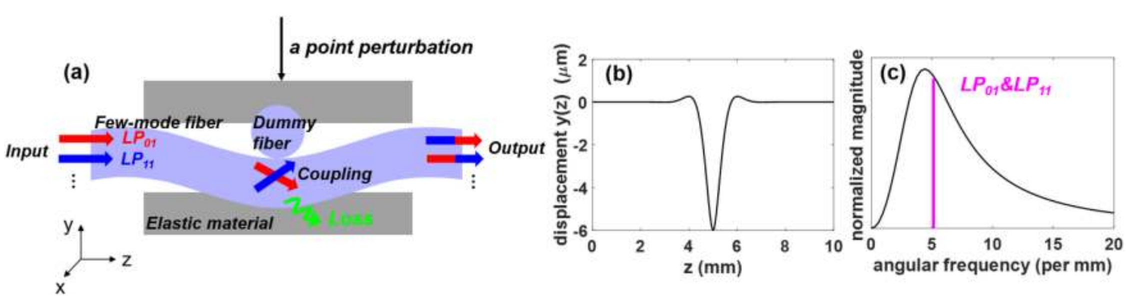

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Wideband and Low-Loss Mode Scrambler for Few-Mode Fibers Based on Distributed Multiple Point-Loads

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Abstract: We propose a new type of all-fiber mode scrambler for mode division multiplexed data transmission based on few mode fibers. By randomly placing multiple point-loads along the fiber length, low loss and wideband mode coupling is obtained amongst all the guided modes. The effect of mode coupling is simulated from a single point-load to multiple point-loads with a specific focus on the insertion loss and wavelength dependence. In an exemplar experimental demonstration we present a mode scrambler for step-index two mode fibers incorporating 150 randomly located point-loads. Uniform mode coupling is achieved over the C band with an insertion loss of less than 1 dB.

Index Terms: Mode scrambler, few mode fiber, mode division multiplexing.

1. Introduction

With conventional single-mode fiber transmission systems rapidly approaching the nonlinear Shannon limit, mode division multiplexing (MDM) based on few-mode fibers (FMFs) or multimode fibers [1], [2] has been intensively investigated to increase the capacity of transmission links. In these MDM transmission systems, the total capacity of the fiber can be drastically increased by a factor corresponding to the number of spatial modes supported by the fiber and MDM transmission over 45 spatial modes [3], [4] has so far been successfully demonstrated. Digital signal processing (DSP) based on multiple-input multiple-output (MIMO) algorithms is typically required at the receiver to recover signals otherwise impaired by the inevitable mode coupling and/or intermodal dispersion within the transmission fiber [5]. However, the computational complexity of the DSP increases with an increase in the number of spatial modes and the intermodal group delay (GD) spread from modal dispersion [6]. Additionally, in a long-haul MDM transmission system, mode-dependent loss (MDL) and/or mode-dependent gain (MDG) among all spatial channels directly affects the system outage probability and limits the achievable transmission distance [7].

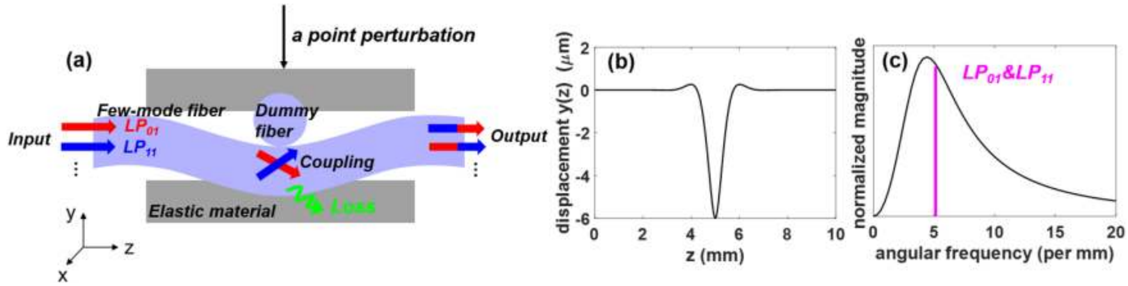

Fig. 1. (a) Schematic of a point-load mode scrambler for few-mode fibers. (b) Fiber displacement along the y-axis under 10 N load and (c) curvature spectrum of a point-load mode scrambler as a function of angular frequency.

Therefore, effective means to reduce the GD spread and MDL/MDG are very important issues in MDM systems.

Recently, it has been reported that strong mode coupling is highly effective in reducing accumulated GD and to improve the overall transmission performance [8]. Moreover, in strongly coupled MDM systems each transmitted signal experiences a nearly identical distribution of power amongst the guided modes which can dramatically mitigate any MDL [9] and ensures that the GD spread is proportional to the square root of the transmission distance [10]. In order to achieve strong mode coupling among all spatial modes various mode scramblers have been studied including those based on long-period gratings (LPGs) [11], phase plates [12], microbends [13] and offset fiber launches [14]. Furthermore, the use of mode scramblers has been investigated as a means to reduce the mode dependent gain (MDG) in few mode fiber amplifiers, for example a 1.8-dB MDG reduction was achieved in a 10-mode fiber amplifier using an LPG based mode scrambler [15]. However, it should be noted that the LPGs have a limited bandwidth (typically ~10 nm) due to the tight phase matching conditions and multiple LPGs with different grating periods are often needed to obtain sufficiently wide bandwidth mode mixing in FMFs. Also, the number of gratings required scales rapidly as the number of guided modes increases in the fiber. Using a large number of LPGs is not cost-effective and device insertion loss also accumulates rapidly.

Here, we propose a new all-fiber mode scrambler based on multiple distributed point-loads with random intervals between load points. Wideband and low-loss characteristics are readily obtained in both simulation and experiment. As a proof of concept, we experimentally demonstrate a mode scrambler for two mode group fiber (supporting the LP_{01} and LP_{11} mode groups) based on 150 load points with random intervals. The mode coupling was uniform over the full C band and the insertion loss was less than 1 dB.

2. Modeling of the Point-Load Mode Scrambler

A schematic of a point-load mode scrambler is shown in Fig. 1(a). By introducing a longitudinal perturbation along a few mode fiber, effective mode coupling among all the guided modes can take place due to microbending or highly localized bending with a sharp curvature. As a point perturbation source in our scrambler, a dummy optical fiber having the same cladding and coating diameter (125 μm and 250 μm, respectively) was placed across the target FMF. The crossover fiber section was sandwiched between two jaws formed of an elastic material and acts as a point perturbation when an external load is applied. For a point perturbation, lateral displacement in the y-direction induces a distortion of the fiber, which is given by [16].

$$y(z) = -\frac{W}{8EI\phi^3} e^{-\phi z}(\cos\phi z + \sin\phi z) \tag{1}$$

where $\phi = (\frac{E_e}{4EI})^{\frac{1}{4}}$, E is the area-weighted average Young's moduli of the coated fiber and E_e is for the elastic material. W denotes the applied load. Also I represents the moment of inertia of the beam, which can be written as $(\pi/4)(r^4)$ for a fiber with the radius of r. According to [17], the strength of mode coupling at the crossover section totally depends on the curvature spectrum of the FMF. The curvature of the fiber c(z) is related to the displacement at longitudinal distance z, which can be expressed as,

$$c(z) = \frac{y''(z)}{\left(1 + y'(z)^2\right)^{3/2}} \tag{2}$$

By calculating the Fourier transform of c(z), we can obtain the curvature spectrum of the fiber as a function of angular frequency.

In our simulation, a simple step-index two-mode group fiber was chosen for mode coupling analysis. The fiber has a core radius of 9.9 μm, a relative index difference of 0.005 and cladding diameter of 125 μm. Young's moduli of the silica cladding and inner/outer polymer coating of optical fibers are typically 72 GPa, 10 MPa and 1.3 GPa respectively, resulting 18 GPa average Young's moduli. Besides, the Young's modulus of the jaw material (e.g., polypropylene) is assumed to be 1.3 GPa, similar to Ref. [16]. For a load of 10 N, the displacement of the two-mode fiber is calculated and presented in Fig. 1(b), which is one-half of the result as calculated from equation (1) due to the equal compression on both jaws. The fiber core deformation occurred within an almost 2 mm section in the axial z-direction and the maximum lateral displacement was ~5.9 μm. Fig. 1(c) shows the calculated curvature spectrum of the fiber. We can see that the spectrum is relatively wide with a central peak of 4.4 mm^{-1} in angular frequency and this is why our point-load mode scrambler can provide effective mode coupling among all the guided modes and a wider spectral bandwidth at the same time. This wide spectral bandwidth ensures that the number of point-load mode scramblers required should not scale rapidly with the number of guided modes. Also note that the mode coupling becomes stronger when the propagation constant difference between the two spatial modes is closer to the central peak position. In our FMF, the propagation constant difference between the LP_{01} and LP_{11} modes was ~ 5 mm^{-1} (purple vertical line in Fig. 1(c) which is close to the peak position of the curvature spectrum, indicating that it can provide efficient mode coupling.

3. Simulation Results

As described above, the degree of mode coupling in a point-load mode scrambler is determined by the curvature spectrum of the fiber. In order to quantitatively evaluate the mode coupling of the FMF, we built a point-load mode scrambler model using RSoft BeamPROP and the detailed mode coupling was studied for single/dual/multiple load points under various loads.

3.1 Single Load Point

Fig. 2 shows the mode coupling of the fiber from a single load point at different loads and its wavelength dependence. The efficiency of the mode coupling gradually increases with applied load and reaches almost 50% when the load is ~10 N for both LP_{01} and LP_{11} mode excitations. Compared to the LP_{01} mode excitation, the insertion loss (IL) of the LP_{11} mode was relatively high (~2 dB at 50% coupling efficiency) due to radiation loss (i.e., most of the light in higher order modes is coupled to other guided modes but it can also couple to highly lossy radiation modes from the microbends). Significantly, the wavelength dependency of the loss and coupling is almost flat over the wide wavelength range spanning the C- and L-bands. A mode scrambler based on a single load point therefore has a rather wide and flat wavelength response but the IL of the device itself should be further improved. The high IL of the single load point is mainly due to the severe fiber deformation and it can be improved by increasing the number of load point and relaxing the requirement of concentrated loads on each load point.

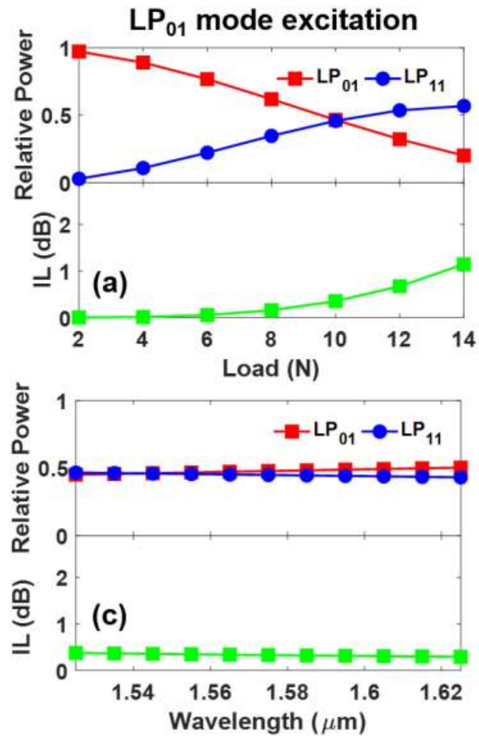

Fig. 2. Mode coupling for a single load point under pure LP$_{01}$ and LP$_{11}$ mode excitation at (a, b) different loads and (c, d) its wavelength dependence at a load of 10 N.

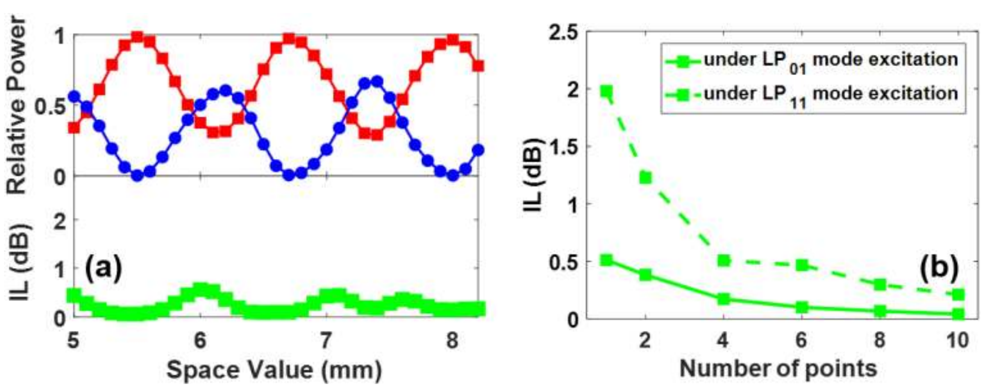

Fig. 3. (a) The effect of distance between two load points under LP$_{01}$ mode excitation and (b) IL vs the number of load points at 12 N.

3.2 Dual- and Multiple Load Points

Next, we focus on the case of dual load points. We find that the distance between the two load points has a great effect on mode coupling and the relative modal power and IL was plotted as a function of distance under LP$_{01}$ mode excitation at 12 N total load (i.e., 6 N each). As shown in Fig. 3(a), the mode coupling efficiency changes periodically as spacing between load points increases and the period is almost equal to the intermodal beat length between the LP$_{01}$ and LP$_{11}$ modes (1.226 mm). In order to maintain a high coupling efficiency, we have fixed the spacing to be 6.1 mm and further increased the number of load points. As one of the key performance parameters, the insertion loss of the mode scrambler was monitored/analyzed according to the

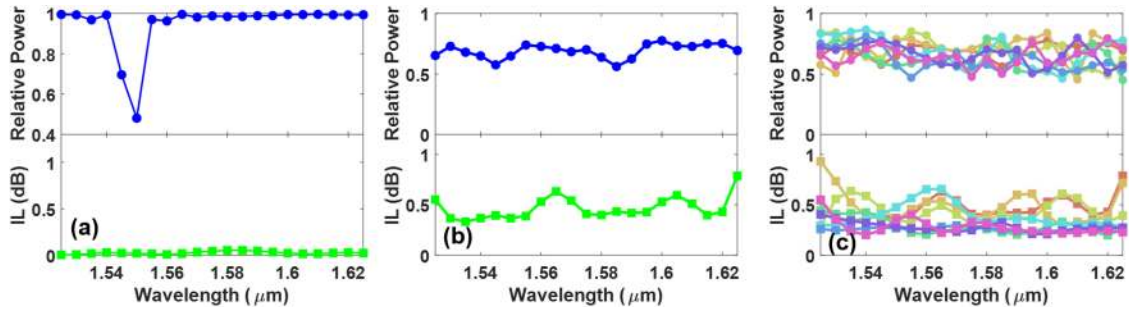

Fig. 4. Wavelength and IL dependence of 66 load points under LP_{11} mode excitation with (a) uniform spacing and (b) with random spacing, and (c) is for multiple choices of random spacing values.

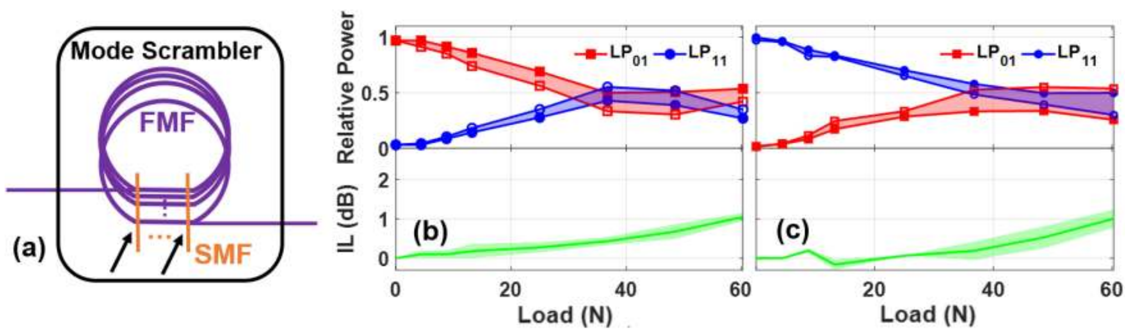

Fig. 5. (a) Schematic of the multi-point-load mode scrambler and the mode coupling properties of 150 load points under (b) pure LP_{01} and (c) LP_{11} mode excitation at different loads.

number of load points, as presented in Fig. 3(b). As the number of load points increases, the IL reduces significantly as expected and it is less than 0.2 dB for both spatial modes when the number of load points exceeds 10.

As well as IL, operational bandwidth is another important issue for mode scramblers. In the case of 66 load points with a fixed spacing of 6.1 mm, we have calculated the relative modal power over the C- and L- band under LP_{11} mode excitation and spectral bandwidth is shown in Fig. 4(a). Even though the IL is pretty low, the device has a very limited operational bandwidth ($\sim$10 nm) because the periodic microbends can be regarded as a kind of LPG. Considering the fact that different spacing values match the mode coupling at different wavelengths, we propose a multi-point-load mode scrambler with random spacing values between load points for wideband operation and low IL. Fig. 4(b, c) shows the wavelength dependence of a 66 load point device with random spacing ranging from 5 mm to 6.226 mm. We plot 8 repeated calculation results in Fig. 4(c) and one of these is shown in Fig. 4(b). Compared to the case of a uniform load point spacing, the bandwidth of the multi-point-load mode scrambler with random spacing values becomes broadband although the IL is slightly increased. We believe that the variation of mode coupling efficiency over the C- and L-bands could be reduced by using a larger number of load points. Overall, a multi-point-load mode scrambler could provide wideband and low-loss characteristic with random distances between load points.

4. Experimental Verification

To verify the wideband and low-loss characteristics, we experimentally set up a multi-point-load mode scrambler with random load point spacings as shown in Fig. 5(a). A step-index two-mode fiber having the same fiber parameters used in our simulation is coiled into $\sim$15 cm fiber loops, and

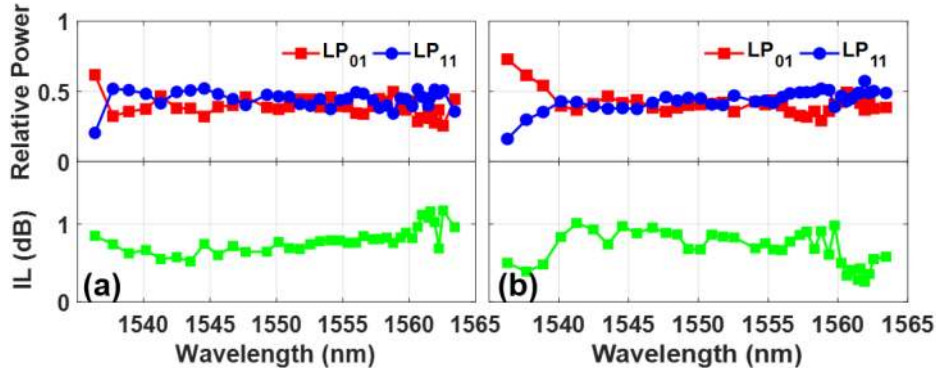

Fig. 6. Wavelength dependence of 150 load points (a) under pure LP_{01} and (b) LP_{11} mode excitation, respectively.

a certain number of dummy optical fibers (e.g., single-mode fibers in our experiment) are randomly placed on the top of the two-mode fiber. The fiber crossover sections are sandwiched between two flat metal plates and a compressive force was applied by adding a static load to the top plate. For a detailed quantitative study of mode conversion, a time-of-flight measurement was used to measure the modal power distribution in the FMF. In our measurement, a picosecond pulsed laser at 1550 nm was used as an input signal pulse and transmitted to the mode scrambler which was applied at the input end of a 10-km two-mode fiber transmission link. As each mode of interest possesses a distinct group velocity light simultaneously coupled into different spatial modes at the fiber input will arrive at the end of the fiber at different times. Therefore, by measuring the impulse response of the link we can readily distinguish different spatial modes with their differential group delays and identify the relative power distributions. In our experiment, a two-mode fiber (without removing its polymer coating) was coiled into 15 loops and 10 crossover fibers were placed across the loops leading to 150 distributed load points. Fig. 5(b, c) show the mode coupling property of the 150 load point mode scrambler under pure LP_{01} and LP_{11} mode excitation as a function of applied load. The colored regions represent the relative power fluctuations of each mode caused by polarization. We find that sufficient mode mixing is introduced when the applied load is close to 40 N (i.e., 0.27 N each), at which the IL is as low $<$1 dB. The wavelength dependency of our multi-point-load mode scrambler was also examined by sweeping the wavelength while maintaining a constant applied force. As shown in Fig. 6, the mode coupling remains relatively constant over the C band even though there is a slight variation in the IL. Furthermore, we also examined the mode coupling characteristic of our proposed mode scrambler based on a step-index four-mode fiber. When the cladding diameter of the crossover fibers is decreased to 80 μm, the peak of the curvature spectrum shifts to match the coupling among all guided modes. The IL can be less than 2 dB at total 48 N load. We believe that high mode scalability for various fibers with different index profiles or geometric sizes could be obtained by flexibly adjusting the peak position of the curvature spectrum (e.g., through the use of different elastic materials or dummy fibers of different size).

5. Conclusion

A multi-point-load mode scrambler was introduced and analyzed in both simulations and experiment. Compared to a single load point device the insertion loss can be significantly improved by increasing the number of load points. However, the distance between load points has a great effect on the mode coupling and it is useful to randomly distribute the load points in order to obtain wide bandwidth. In our experiment, a two-mode fiber mode scrambler was successfully realized with 150 randomly located load points. The mode scrambler offers stable and relatively uniform performance over the C band and a low insertion loss of less than 1 dB. Multi load point scramblers have a wide curvature spectrum and they are expected to be applicable to optical fibers with a large number of spatial modes and to be able to provide high quality simultaneous mode coupling among all these modes.

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