Variable optical attenuator and dynamic mode group equalizer for few mode fibers

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Abstract: Variable optical attenuation (VOA) for three-mode fiber is experimentally presented, utilizing an amplitude spatial light modulator (SLM), achieving up to −28dB uniform attenuation for all modes. Using the ability to spatially vary the attenuation distribution with the SLM, we also achieve up to 10dB differential attenuation between the fiber's two supported mode group (LP_{01} and LP_{11}). The spatially selective attenuation serves as the basis of a dynamic mode-group equalizer (DME), potentially gain-balancing mode dependent optical amplification. We extend the experimental three mode DME functionality with a performance analysis of a fiber supporting 6 spatial modes in four mode groups. The spatial modes' distribution and overlap limit the available dynamic range and performance of the DME in the higher mode count case.

OCIS codes: (060.2340) Fiber optics components; (060.2330) Fiber optics communications.

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1. Introduction

Mode division multiplexing (MDM) has attracted great attention in the last few years as a viable solution for increasing the information capacity of optical fibers [1]. A whole suite of innovations is being introduced in support of MDM transmission, including few mode fibers (FMF) with optimized transmission characteristics [2], efficient optical multiplexing schemes [3–6], and fiber amplifiers [7–10]. In this work we present an adaptive attenuator that can attenuate uniformly all the fiber propagating modes, serving as a Variable Optical Attenuator (VOA), as well as selective attenuation by mode groups, realizing a Dynamic Mode group Equalizer (DME). Both functions are requisite components in FMF transmission systems, just as their single mode counterparts are: single mode VOA and dynamic gain equalizers (DGE).

Single mode fiber VOAs are often placed at the receiver input, reducing the dynamic range of the received optical power at the photo-detector. A typical implementation consists of a free-space implementation with a MEMS angle steering mirror [11], which incurs excess loss as the optical beam is detuned further from the output fiber core. However the same approach cannot be employed for the FMF case, as each mode experiences unique attenuation as a function of offset detuning as well as mode mixing as orthogonality is not preserved under these conditions (Fig. 1); these effects give rise to mode-dependent loss (MDL) and information loss. Our FMF-VOA eliminates the modal dependence by employing an attenuation mechanism based on liquid-crystal polarization rotation, which can attenuate the reflectivity uniformly and not introduce any spatial offsets which give rise to mode mixing and MDL.

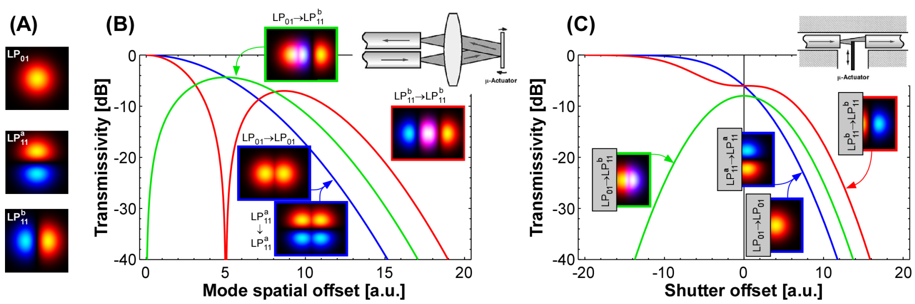

Fig. 1. Application of SMF-VOA solutions to FMF resulting in uneven mode attenuation and mode mixing. (A) Three spatial fiber modes. (B) VOA by MEMS beam steering. The imaged beam is detuned from the fiber facet, resulting in overlap integral between offset modes. (C) VOA by MEMS shutter. The beam is clipped, resulting in overlap integral over the remaining beam regions.

FMF erbium-doped amplifiers are vital to the successful adoption of MDM transmission. A critical design consideration for these fiber amplifiers is the minimization of differential-mode gain (DMG, equivalent in significance to MDL). Special erbium-doping radial concentrations and pumping schemes are being employed in attempt to minimize DMG, with recent publications demonstrating 4-5 dB DMG [7–10]. This DMG can be dynamically compensated with a mode-dependent loss mechanism. Our attenuator is based on a liquid crystal on silicon (LCoS) spatial light modulator (SLM), in a twisted nematic configuration for attenuation control with a polarization analyzer. The LCoS SLM allows us to prescribe different attenuation values across the aperture. Owing to the distinct fiber mode profiles, by applying a spatially-varying attenuation profile we can selectively attenuate the polarization degenerate LP_{01} mode or the two-fold degenerate LP_{11} modes (polarization and rotation angle) over a finite dynamic range. An alternative embodiment for wavelength dependent mode equalization was presented in [12], based on processing spatially dispersed light with an LCoS SLM. However the efficacy of this approach is limited, as access to specific spatial modes is restricted in spatially dispersed light, resulting in spatial mode and temporal frequency coupling.

The optical design of the spatial attenuator we constructed with support for three mode fiber and its operation as a VOA and DME is described in the next section, followed by a reporting of the experimental results. Then we study by simulation the scaling potential of the DME, for the case of a fiber supporting six spatial modes in four mode groups. The study indicates that even when attempting to use more complicated attenuation patterns, high values of mode-selective attenuation cannot be obtained with a spatial masking function, and will impact the other propagating modes with undesired attenuation and mixing.

2. Few mode fiber spatial attenuator design

The free-space arrangement of our spatial mode attenuator is shown in Fig. 2(a). The input/output three-mode fibers have mating lenses for collimating/focusing the light from/into the fiber. Since we employ an LCoS polarization rotation SLM, serving as an amplitude modulator, the incident light has to be linearly polarized. A conventional polarization-diversity scheme is used, separating each fiber beam containing the three modes to two distinct beams that are set to the same polarization with the aid of a half waveplate. The four beams (input/output × two polarizations) are focused by a single lens onto a common location on the LCoS SLM at the lens back focal plane. To efficiently utilize the SLM for mode selective attenuation settings, the lenses' focal lengths are chosen such that the fiber modes are magnified on the SLM, hence illuminating many pixels and providing good spatial resolution. In our implementation the imaged and magnified fiber mode diameter is roughly equal to 450 pixels (pixel pitch is 8 μm).

The performance of the mode-selective attenuator is characterized using a modified swept laser interferometry technique [13]. A commercial, single mode optimized optical vector analyzer (OVA) is used in conjunction with our own free-space mode excitation multiplexer and demultiplexer based on spatial phase masks for mode conversion, with individual paths encoded by unique propagation delays and power equalized with conventional SMF-VOAs (Fig. 2(b)). The FMF device under test (DUT) is placed within the measurement system, which scans across all possible mode and polarization states. The generated 2×2 Jones matrix elements (per wavelength) obtained from the OVA are processed off-line, separating and retiming each distinct path (total of nine possible paths, each characterized by a 2×2 Jones matrix), and then populating (per wavelength) a sub-matrix within the 6×6 matrix describing the input/output dependence per each mode (LP_{01} and degenerate LP_{11}, with two polarizations each). From the eigenvalues of this 6×6 input/output transfer matrix we find the average modal insertion loss (IL) and MDL.

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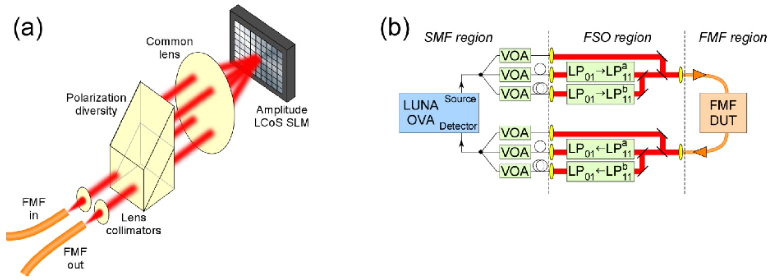

Fig. 2. (a) Polarization-diverse free-space optical arrangement of dynamic mode-group optical attenuator with amplitude spatial light modulator. (b) Experimental characterization technique using swept laser interferometry, obtaining full device complex matrix response.

3. Experimental results

The spatial attenuator was first utilized as a VOA, uniformly attenuating all incident light. Different attenuation values were applied and the average IL increased uniformly (Fig. 3). The attenuation tuning range increased until we reached the noise floor of our measurement system, at about –28 dB attenuation, due to excess loss at the mode multiplexer and demultiplexer, each contributing about 16 dB additional loss (due to splitter and other loss sources). The LCoS attenuation range was independently characterized (without the modal measurement system) as being able to provide at most –28 dB loss, with the limitation being the weak cover glass reflection. The FMF VOA exhibited MDL values that did not change significantly as the attenuation increased, with nearly constant background MDL of 4 dB originating from the measurement system itself. MDL does start to spike when attempting to characterize at the highest attenuation, due to dominant measurement noise. The VOA average IL (at no attenuation setting) is –4.3 dB, of which 2 dB are assigned to the LCoS SLM.

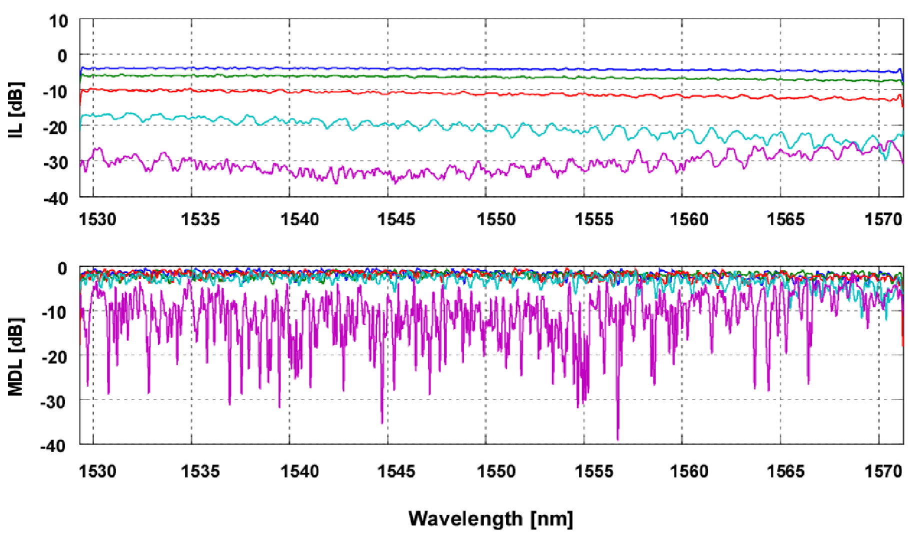

Fig. 3. FMF-VOA functionality. A) Flat response of attenuation over 25dB of attenuation. B) MDL at different attenuation values. MDL shows no increase until attenuation level reaches noise floor. Observed constant MDL is that of mux/ demux system; VOA settings do not alter it.

Next, spatial patterns were applied across the SLM to obtain DME functionality. The intensity pattern of LP_{01} mode is Gaussian-like concentrated in the center of the fiber, whereas the degenerate LP_{11} mode group is doughnut-like. Therefore, when attenuating within the central region with a blocking circle we impact the fundamental mode much more than the higher order LP_{11} mode group, and vice versa (with a circular aperture).

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Simulation of binary and graded transition blocking circles or transmitting apertures of varying radii were performed for the optimization of specific mode attenuation. The largest mode difference of almost 10 dB was obtained with the binary edge.

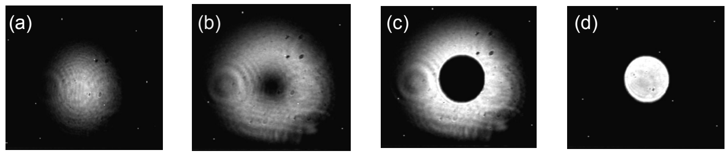

Fig. 4. NIR images of reflected optical beam from LCoS SLM. a) LP01 mode excitation, b) LP11 mode group excitation, c) both mode groups illuminate SLM with circular block attenuation pattern applied for predominantly LP01 suppression and d) both spatial mode groups with circular aperture attenuating pattern for LP11 suppression.

Figure 4 shows images collected from reflected light coming off the SLM, showing the illumination of either the LP_{01} or LP_{11} mode groups, as well as the circular block and circular aperture attenuation patterns applied to both modes groups. The circular block significantly overlaps with the fundamental LP_{01} mode group, whereas the circular aperture significantly overlaps with the LP_{11} mode group.

When realizing the binary and the graded transition patterns we achieved results matching very well to theory. The IL per mode group is depicted in Fig. 5, as obtained from the simulation (top) and from the modal characterization tool (bottom). These experimental IL values are extracted from the 6 × 6 matrix describing the input/output modal dependence, with the IL of the LP_{01} mode determined by the eigenvalues of the top-left 2 × 2 elements, and the IL of the LP_{11} modes determined by the eigenvalues of the bottom-right 4 × 4 elements. As expected, we can induce mode-dependent losses by our blocking circles and transmitting apertures, with up to 9.3dB relative loss between the mode groups (whether in favor of LP_{01} or LP_{11} modes).

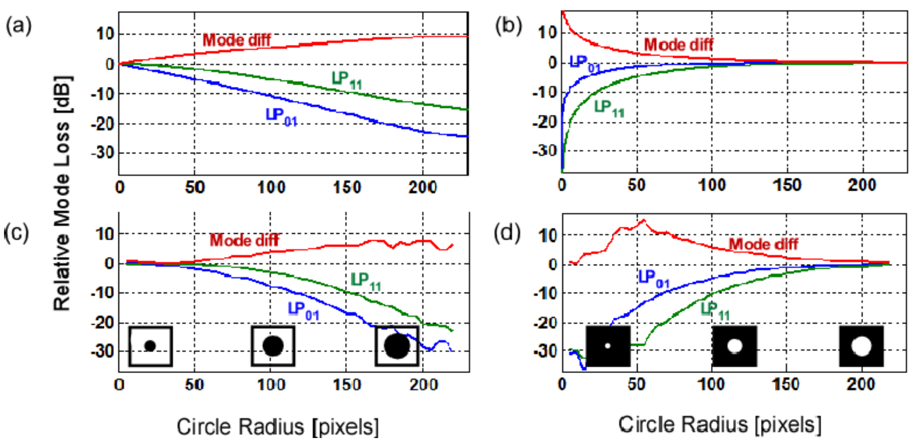

Fig. 5. Dynamic mode group equalizer responses. (a-b) Simulation and (c-d) measurement results of attenuation, employing a blocking circle (a, c) or blocking aperture (b, d) pattern. As the blocking radius increases, both modes attenuate, with the LP01 incurring significant loss earlier. For the circular apertures, both modes' transmission increase with aperture radius, with the LP01 transmission rising earlier.

4. Attenuation simulation for higher mode counts

As the fiber's normalized frequency (V-number) increases and more mode groups are guided, more spatially complicated modes are involved. While the VOA performance is unaffected by this, as uniform attenuation is applied, greater difficulty at mode selective attenuation is expected. The DME functionality was investigated for FMF supporting four mode groups (polarization degenerate LP_{01} and LP_{02}, and the doubly degenerate LP_{11} and LP_{21} mode groups. See Fig. 6). As in the three mode fiber simulation, we calculate the output field distribution of each mode after being attenuated by the SLM and calculate the fiber coupling overlap integral after attenuation for each input mode to each output mode and construct a mode transfer matrix characterizing the DME functionality. (The fiber coupling between the i'th input mode and the j'th output mode is denoted ξ_{ij}). Since each mode group has a different effective area and spatial distribution, the attenuation pattern should be optimized in order to obtain the required DME functionality.

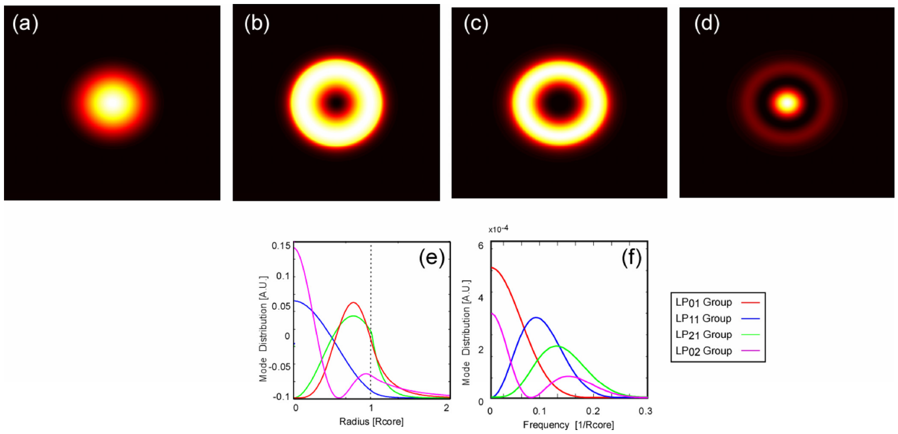

Fig. 6. Intensity patterns of the first four mode groups in a six mode fiber: (a) LP01 mode (b) LP11 mode group (c) LP21 mode group and (d) LP02 mode. (e) Radial mode intensity distribution of the four mode groups. Dashed vertical lines denotes the core-cladding interface. (f) Radial Fourier transform intensity distribution of the four mode groups.

For attenuation targeted at specific modes, while reducing the impact to the remaining modes, the attenuation patterns applied by the LCoS SLM have to be best matched to the targeted mode. Since we are targeting the attenuation of mode groups, all of which have circular symmetry, the blocking shapes must also have circular symmetry to prevent MDL within the mode groups. Hence the attenuation patterns are defined by their radial distribution only, and are circularly symmetric, hence they do not change the angular momentum of the filtered modes. Thus the attenuation patterns cannot result in modal crosstalk between mode groups with different angular momentum. In our four mode group study case, only the LP_{01} and LP_{02} have the same angular momentum and are therefore susceptible to mixing between them. This implies that the mode transfer matrix of the DME is a diagonal matrix (with elements ξ_{11}, ξ_{22}, ξ_{33}, and ξ_{44}), and two equal, non-diagonal elements ξ_{14} and ξ_{41} which result from mode mixing between the LP_{01} and LP_{02} mode groups.

The DME functionality is required to compensate for possible mode power imbalance arising from other elements in the transmission system, specifically an FMF-EDFA. To synthetically assess the DME performance, we first construct a complete system comprising the EDFA and associate its DMG with one specific mode, to be followed by the DME's mode transfer function. The DMG of the EDFA is modeled as a diagonal matrix with all elements equal to one except for one element that experienced the greater gain. In order to demonstrate this point we chose extreme scenarios in which we try to adjust one spatial mode at a time only, with minimal impact on remaining ones: For example, if the fundamental mode experienced double the power gain of the other modes, then the mode evolution through the system would be defined by Eq. (1):

$$\begin{bmatrix} \hat{\varphi}_1 \\ \hat{\varphi}_2 \\ \hat{\varphi}_3 \\ \hat{\varphi}_4 \end{bmatrix} = \underbrace{\begin{bmatrix} \xi_{11} & 0 & 0 & \xi_{14} \\ 0 & \xi_{22} & 0 & 0 \\ 0 & 0 & \xi_{33} & 0 \\ \xi_{41} & 0 & 0 & \xi_{44} \end{bmatrix}}_{\text{DME}} \underbrace{\begin{bmatrix} \sqrt{2} & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{\text{DMG}} \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \end{bmatrix} \tag{1}$$

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Without the DME, the fundamental mode would have twice the power of the remaining modes. The role of the DME is two-fold: to better balance the modal powers, $|\hat{\varphi}_i|^2$, and reduce the system MDL which is provided by the eigenvalues of the system matrix (product of the DMG and DME matrices). It is important to note that the DMG modelling used herein is generic and probably not well-representing a real FMF-EDFA. An EDFA's actual DMG arises in a distributed process along the amplifier length, depending on the erbium radial doping profile and pumping scheme [15–16]. The DME attempts to correct the DMG with a lumped system consisting of the spatial mask and its associated mode transfer function.

The DME functionality was assessed for compensation of 3dB DMG, applied to each mode separately. In each equalization attempt we try to reduce the modal power imbalance (from an initial 3dB value) and MDL (again, from an initial 3dB value), and desire low average losses. The attenuation patterns investigated consisted of blocking circles and rings or aperture circles and rings, varying the radii (see Fig. 7, plotting the mode transfer matrix values squared, the self-terms and the LP_{01}-LP_{02} crosstalk power). Grayscale patterns did not achieve better discrimination, nor did attempts to match the intensity distribution. Since the modes' field distributions substantially overlap, it can be difficult to target a specific mode without influencing the others. Filtering of the spatial modes can be done either in the image plane or Fourier plane. In both cases, the overlap between the modes of their Fourier transform leads to similar results.

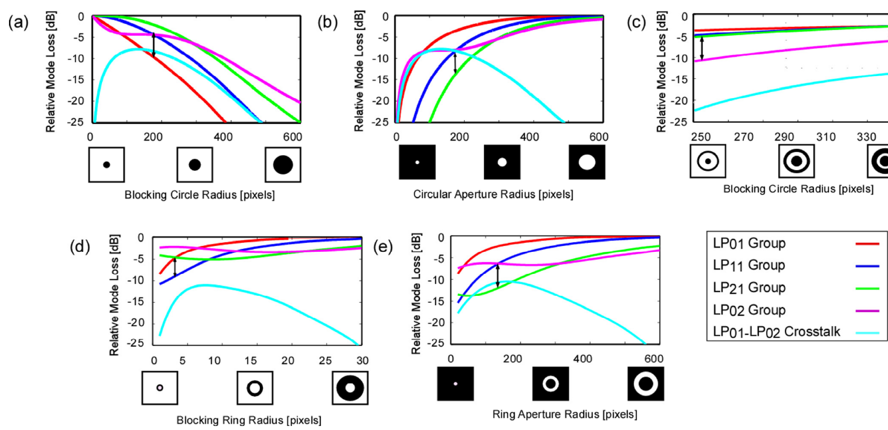

Fig. 7. Dynamic mode group equalizer response simulations for a six mode fiber. Blocking and transmitting annular patterns for specific mode attenuation:(a) attenuating LP01 mode (b) attenuating LP21 mode (c) attenuating LP11 mode (d) attenuating LP21 mode (e) attenuating LP02 mode

Balancing the modal powers, $|\hat{\varphi}_i|^2$, is possible using the above mentioned patterns. Imbalance of 3 dB in favor of LP_{01} was reduced to 1.4 dB with average insertion loss of 1.5 dB. In the LP_{02} mode case, 3 dB difference can be reduced to 0.7 dB, with average IL of −2.3 dB. Imbalance of 3 dB in favor of LP_{11} and LP_{21} was reduced to 2.3 dB and 2 dB with average IL of 1.4 dB and 0.9 dB respectively. As can be seen above, LP_{11} and LP_{21} modes are difficult to separate, as most of their field distribution overlap as well as their Fourier transform distributions (Fig. 7(e), 7(f)). On the other hand, attenuation of the two modes together is very effective (assuming both are magnified by 3 dB) and achieves 0.35 dB imbalance with 0.9 dB IL. As the similarity between LP_{11} and LP_{21} is expected to respond in the same way to the EDFAs' MDG, attenuating them both can be a useful. The results calculated $|\hat{\varphi}_i|^2$, without taking into account the information loss caused by crosstalk. In order to do this, the eigenvalues of the transfer matrix were extracted. The eigenvalues represent the actual data stream in each channel (each spatial mode).

The best DME results we obtained were when trying to attenuate the higher power LP_{02} mode. The MDL was reduced to 1.75 dB, keeping the average excess loss less than

–2 dB. Targeting the LP_{02} is possible using a double ring pattern that attenuates the outer part of the internal lobe and much of the external one. When trying to attenuate the LP_{11} mode, the MDL was reduced to 1.6 dB, but the average excess loss is ~-3.8dB. LP_{11} attenuation was realized by a single ring pattern in the narrow area of low intensity of LP_{02} mode. MDL reduction when the LP_{01} and LP_{21} were dominant was very minor. The explanation of this lies in the mode field distributions. The two limiting factors are the overlapping modes' distributions and the crosstalk between the LP_{0n} modes. The former prevents addressing the LP_{21} mode, and the latter couples any attenuation of the LP_{01} mode to the LP_{02} mode. Although the LP_{11} and LP_{21} modes were thought to be efficiently attenuated together, the crosstalk induced is very high.

5. Conclusions

The first realization of a spatial attenuator mated to a three mode fiber has been reported. The system can be operated as a VOA with 4.3 dB IL, capable of attenuating to the LCoS limit of –28 dB with no significant increase of MDL (until the noise floor of our measurement system is reached). The system can further be operable as a DME, selectively attenuating the LP_{01} or LP_{11} mode groups with 10 dB mode group equalization range. FMF supporting four mode groups was investigated in order to understand the influence of guiding more modes in terms of efficiency, MDL and modal crosstalk. Our simulations indicates strong crosstalk between modes with the same angular momentum, and poor discrimination between specific modes. Some modes can obtain sufficient DME range, but the restriction of crosstalk together with the modes' distribution limits the effect over other modes.

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