Enhancing mode stability of higher order modes in a multimode fiber

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Abstract: An innovative strategy to increase the modal stability of the higher order modes of multimode fiber is proposed where the modal stability is increased by more than 80% between LP_{05} and its neighboring antisymmetric modes.

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1. Theory and numerical results

A larger multimode fibers (MMF) offers an increased mode area, which is less susceptible of nonlinearities in the fiber [1,2]. However, due to existence of many modes in a MMF, the chances of mode coupling between a desired mode of operation and its nearest antisymmetric modes also increases [3]. The modal stability Δn_{eff} between the preferred mode of propagation LP_{0m} and its neighboring antisymmetric LP_{1m} modes increases with the increase in modal order (m) which results in less mode coupling. In this paper we have proposed an innovative concept to enhance the stability of higher order mode LP_{05} by increasing its effective index difference (Δn_{eff}) with its neighboring antisymmetric LP_{14} and LP_{15} modes. For our simulations we have used full-vectorial **H**-field modal solution approach [4] to study a MMF with core radius of 25 μm, numerical aperture (NA = 0.22) and operating wavelength of λ=1.05 μm.

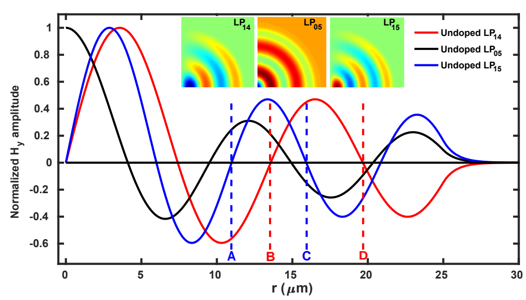


Fig. 1: Variations of H_y fields of the LP_{14}, LP_{05}, and LP_{15} modes along the r-axis of the MMF, contour field profiles are given as insets and the key locations of interest are also shown.

Table 1: Zero crossing locations along the radius of multimode fiber where the H_y field values of LP_{14}, LP_{05} and LP_{15} modes are zero.

Higher order optical modes	**Effective index (n_{eff})**	**Zero crossing locations along r-axis** (μm)				
LP_{14}	1.45443491	0	7.357	13.525	19.60	31.529
LP_{05}	1.45378140	4.08	9.488	14.875	20.275	31.88
LP_{15}	1.45308231	0	5.94	10.916	15.839	20.757

Figure 1 shows the variation of the dominant normalized H_y field profiles of the LP_{05} and two adjacent antisymmetric LP_{14} and LP_{15} modes. The H_y contour field profiles of these modes are also shown in Fig. 1 as insets. The LP_{05} mode has the peak value at r = 0 and it crosses zero values on four different locations along the fiber radius. Similarly, the LP_{14} and LP_{15} modes have zero field value at the center (r = 0) and have three and four zero crossings along the radius of the fiber as shown in Table 1, respectively. Four strategically located locations (A, B, C and D) are chosen where either LP_{14} or LP_{15} mode has zero field values. An annular strip with width 0.4 μm and $\pm\Delta n = 0.0167$ is introduced at the above mentioned points and corresponding $S_1 = \Delta n_{eff}(LP_{14} - LP_{05})$ and $S_2 = \Delta n_{eff}(LP_{14} - LP_{05})$ are calculated. Here, for strip doping we have taken the $\Delta n = 0.0167$, equal to the difference between core and cladding refractive indices of the MMF. The effective indices of the modes increases or decreases for Δn positive or negative, respectively, and its value depends on the field value of the corresponding modes at that particular location.

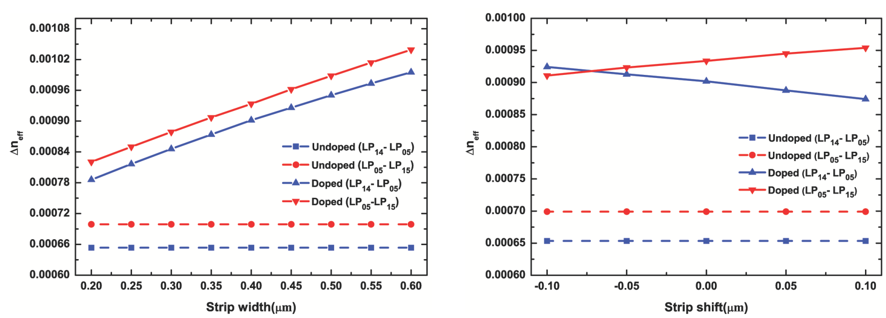
Here, we report percentage increase in the modal stabilities using single or a combination of strips as shown in the Table 2. When a single strip of $-\Delta n = 0.0167$ is introduced at point B = 13.252 μm the modal stabilities S_1 and S_2 are increased by 38% and 34%, respectively. It should be noted here that at point B, the field value of LP_{14} mode is zero hence, any strip doping has very little effect on the effective index of the LP_{14} mode. However, the effective index of the LP_{05} and LP_{15} modes are reduced depending on the modal field values as shown in Fig.1. Similar approach is conducted with two $-\Delta n$ doped strips at points B and D and the resultant modal stabilities increased to $S_1 = 45\%$ and $S_2 = 57\%$ as shown in Table 2. Moreover, with the combination of three strip dopings at points (A=+Δn), (B=−Δn) and (C=+Δn) the modal stabilities S_1 and S_2 are increased to 103% and 83%, respectively.

Table 2: Percentage increase in the $\Delta n_{eff}(LP_{14}-LP_{05})$ and $\Delta n_{eff}(LP_{05}-LP_{15})$ by individual and combination of doped strips.

Modal stability	**Without doping**	**B^- layer only**		**B^- & D^- layers**		**A^+, B^- & C^+ layers**	
		Δn_{eff}	**% Increase**	**Δn_{eff}**	**% Increase**	**Δn_{eff}**	**% Increase**
$S_1 = LP_{14}-LP_{05}$	0.00065351	0.00090188	38	0.00094974	45	0.00132629	103
$S_2 = LP_{05}-LP_{15}$	0.00069908	0.00093364	34	0.00109850	57	0.00127630	83

2. Fabrication tolerance

Figure 2 (a) shows the modal stability improves with the strip width. Figure 2 (b) shows the effect on the modal stability improvement with the shift of strip from the center point B for a single layer doping. It can be observed that with the width change of ±0.1 μm, the modal stability improvement remains above 25%. Similarly, for the strip shift of ± 0.1 μm from center point B the modal stability improvement remains above 30%.



(a) (b)

Fig. 2: Effect on the Δn_{eff} improvement by the variation of (a) strip width and (b) strip position from central point for a single layer at point B.

3. Conclusions

We have proposed an innovative approach to increase the modal stability of HOM of MMF. We have achieved 34% improvement in the modal stability by using a single doped layer and more than 80% when three doped layers are used. The technique is scalable and can be applied to increase the modal stability of other higher order modes if required. We have also shown that our proposed design is significantly stable to possible fabrication tolerances.

References

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