Modal sensitivity analysis for single mode operation in large mode area fiber

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ABSTRACT

Most of the current large mode area (LMA) fibers are few-moded designs using a large, low numerical aperture (N.A.) core, which promotes mode coupling between core modes and increases bending losses (coupling with cladding modes), which is undesirable both in terms of mode area and beam quality. Furthermore, short LMA fiber lengths and small cladding diameters are needed to minimize nonlinear effects and maximize pump absorption respectively in high-power pulsed laser systems. Although gain fiber coiling is a widely used technique to filter-out unwanted modes in LMA fibers, coupling between modes can still occur in component leads and relay fibers. In relay fiber, light coupled into higher-order modes can subsequently be lost in the coiling or continue as higher-order modes, which has the overall effect of reducing the effective transmission of the LP_{01} mode and degrading the beam quality. However, maximum transmission of the LP_{01} mode is often required in order to have the best possible beam quality (minimal M^2). Launching in an LMA fiber with a mode field adapter (MFA)[1] provides an excellent way of ensuring maximum LP_{01} coupling, but preservation of this mode requires high modal stability in the output fiber. Small cladding, low N.A. LMA fibers have the disadvantage of being extremely sensitive to external forces in real-life applications, which is unwanted for systems where highly sensitive mode coupling can occur. In this paper, we present a detailed experimental and theoretical analysis of mode coupling sensitivity in LMA fibers as a function of fiber parameters such as N.A., core diameter and cladding diameter. Furthermore, we present the impact of higher N.A. as a solution to increase mode stability in terms of its effect on peak power, effective mode area and coupling efficiency.

Keywords: Large mode area fibers, fiber lasers, amplifiers, single-mode operation, mode sensitivity, mode coupling, bent fibers.

1. INTRODUCTION

High power optical fiber systems, whether they constitute an amplifier or laser, continuous wave (CW) or pulsed, have to withstand considerably high power densities in the core region. In particular, pulsed laser systems can generate extremely high peak field values thus generating non-linear effects such as self-phase modulation (SPM) and four-wave mixing (FWM).[2] Therefore, one way of reducing those effects is to lower the power density per unit area, which would decrease the maximum field value. Aside from the power and field intensity considerations mentioned earlier, preservation of the beam quality is another very important aspect of fiber lasers and amplifiers in a multitude of applications. Modal content in the fiber and its preservation is thus of utmost importance to ensure that the focalized spot-size is as close as possible to the Fourier limit of a Gaussian beam, which has an M^2 equal to 1.[3] This implies that mode coupling in the fiber has a negative impact on the beam quality since all higher-order modes have an M^2 value larger than the LP_{01} mode and the effective M^2 and pointing accuracy are strongly dependent on modal content.[3]

The harmonization of the main two objectives presented here, which are to lower the power density (and field amplitude) while preserving single-mode operation[4] and prevent mode coupling, have led optical fiber designers to design large modal area (LMA) optical fibers which frequently consist of a large core (in comparison to the wavelength) and a very low N.A. The objective of those two design parameters are to enlarge the effective mode area (and thus reduce the power density) and limit the number of modes supported by the fiber. In general, such fibers facilitate the promotion of LP_{01} gain over other modes in the gain fiber simply by coiling at an appropriate radius (function of the

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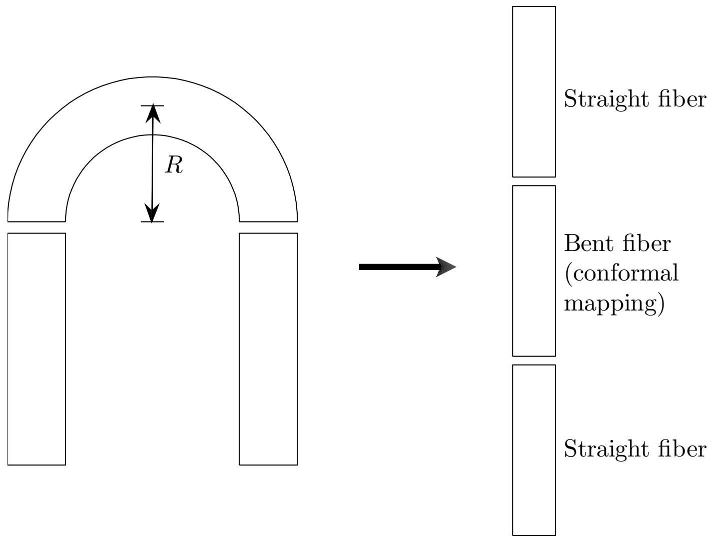


FIG. 1. Illustration of the conformal mapping of the bent fiber with bend radius R. The bent fiber scenario on the left is transformed into the straight fiber equivalent on the right through coordinate transformations. This approach is particularly useful in order to perform numerical calculations of the mode structure in the bent fiber by directly applying the theory developed for straight fibers.

fiber parameters) since all higher order modes have higher bend loss, based on a multitude of bend loss models which stipulate that the attenuation coefficient 2α for a given mode is related to the guiding efficiency[5] $\eta = P_{\text{core}}/P$:

$$2\alpha \propto \frac{P_{\text{clad}}}{P} = 1 - \eta \qquad (1)$$

Although the large core, low N.A. fiber design is very efficient and extremely popular in amplifiers and laser systems because of its convenience, the use of gain-fiber-matched LMA fibers in components such as multi-mode pump combiners tend to be problematic and hazardous in terms of beam quality preservation. The fiber laser and amplifier industries require insertion loss specifications on the LP_{01} mode, which can be measured with the use of the MFA technology,[1] providing high-efficiency coupling in the fundamental mode (typically ranging from 0.25 dB to 0.5 dB) in a two-way fashion. With the currently available combiner technologies, we have noticed that "ideal" LMA fibers (with very low N.A.) tend to be extremely sensitive and can have a significant impact on the fabrication process. In this paper, we present an extensive analysis, both experimental and theoretical, of fiber sensitivity to bending and mode-coupling as well as a quantification of the impact of using higher N.A. LMA fibers in components in terms of mode matching and beam-quality preservation.

2. MODAL STRUCTURE IN BENT LMA FIBERS

In this section, a review of mode-related effects in bent LMA fiber is performed, especially in terms of scalability relative to N.A. A comprehensive theoretical analysis is performed and experimental comparative results are presented.

2.1 Mode scalability in bent LMA fibers - definitions

Understanding of scalability parameters in optical fiber is important for our study. Some extensive work in expressing the behavior of bent fibers in terms of normalized parameters has been conducted by Ross T. Schermer[6] and will help define the necessary basis for our analysis. The two main normalized parameters that will be used in our analysis are the V-number[7] and the $\mathfrak{R}$-number,[6] which are defined as follows :

$$V \equiv kR_{\text{co}}\text{N.A.} \tag{2}$$

$$\mathfrak{R} \equiv R_{\text{eff}}k_{\text{clad}}\left(\frac{\text{N.A.}}{n_{\text{clad}}}\right)^3 \tag{3}$$

where $k = 2\pi/\lambda$ is the propagation constant of light in vacuum, R_{co} is radius of the fiber core, $\text{N.A.} = \sqrt{n_{\text{co}}^2 - n_{\text{clad}}^2}$ is the step-index numerical aperture, R_{eff} is the effective bend radius (taking the stress-induced refractive index change into account ; $R_{\text{eff}} \approx 1.27R$ for silica, where R is the true bend radius[6]) and $k_{\text{clad}} = n_{\text{clad}}k$ is the propagation constant in the cladding. It can be shown that scalability between bent fibers depends on both V and $\mathfrak{R}$.[6] Another extremely useful parameter to use in the stability and scalability of the modal behavior between bent fibers with different V parameters and bend radius is the normalized propagation constant, b_s given by :

$$b_s \equiv \frac{n_{\text{eff},s}^2 - n_{\text{clad}}^2}{\text{N.A.}^2} \tag{4}$$

where the subscript "s" denotes the value of the parameters in the straight (unbent) fiber. The study of the impact of bending the fiber is performed through the use of conformal mapping (as shown on Fig. 1), allowing the conversion of the behavior of the bent fiber to a straight fiber equivalent.[8] In order to perform the conformal mapping from the bent fiber to the straight fiber equivalent, the coordinate system r, θ must be mapped to another system x, z according to the following equations (y is the coordinate orthogonal to the coiling plane) :

$$x \approx r - R \tag{5}$$

$$z = R\theta \tag{6}$$

$$n(x,y) \approx n_0(x,y)\left[1 + \frac{x}{R_{\text{eff}}}\right] \tag{7}$$

With the use of conformal mapping, it is possible to compute the modal structure propagating through the bend with constant angular phase velocity,[6] which is a conceptual equivalent to conventional modes in a straight fiber. With the mathematical tools described here, one can calculate the mode structure of the bent LMA fiber and estimate the scaling of the mode sensitivity through the scaling of the modal structure itself. Note though that the propagation constants of the modes in the bent fibers normally have a slight imaginary part since all modes in a bent fiber are leaky to a certain extent. Analogous to the normalized propagation constant in straight fiber, a similar quantity, b_b can be defined for bent fibers :

$$b_b = \frac{\left(\frac{\text{Re}(\beta)}{k}\right)^2\left(\frac{R}{R+R_{\text{co}}}\right)^2 - n_{\text{clad}}^2}{\text{N.A.}^2} \tag{8}$$

2.2 Bend loss calculation in LMA fibers

A multitude of theories and formulas exist for bend loss calculation in optical fibers.[5,9] Although those formulas are often adequate to predict bend loss in single mode optical fibers, they tend to over-estimate the loss in multimode fibers. A hybrid analytical approach using propagation constant values obtained through numerical mode solving has proven to be considerably more accurate for multimode LMA fibers.[10] The formula used to compute the power loss coefficient 2α is given by :

$$2\alpha = \frac{\sqrt{\pi}\kappa^2 \exp\left[-\frac{2\gamma^3(R+R_{\text{co}})_{\text{eff}}}{3\beta^2}\right]}{2\sqrt{(R+R_{\text{co}})_{\text{eff}}}\gamma^{3/2}V^2K_{\ell-1}(\gamma R_{\text{co}})K_{\ell+1}(\gamma R_{\text{co}})} \tag{9}$$

where

$$\kappa = \sqrt{k_{\text{co}}^2 - \beta^2} \tag{10}$$

$$\gamma = \sqrt{\beta^2 - k_{\text{clad}}^2} \tag{11}$$

$k_{\text{co}} = n_{\text{co}}^2 k^2$, n_{co} is the refractive index of the core, R_{co} is the fiber core radius and K_ℓ is the modified Bessel function of the second kind, with ℓ corresponding to the order of the mode $\text{LP}_{\ell m}$. Figure 2 illustrates examples of the mode

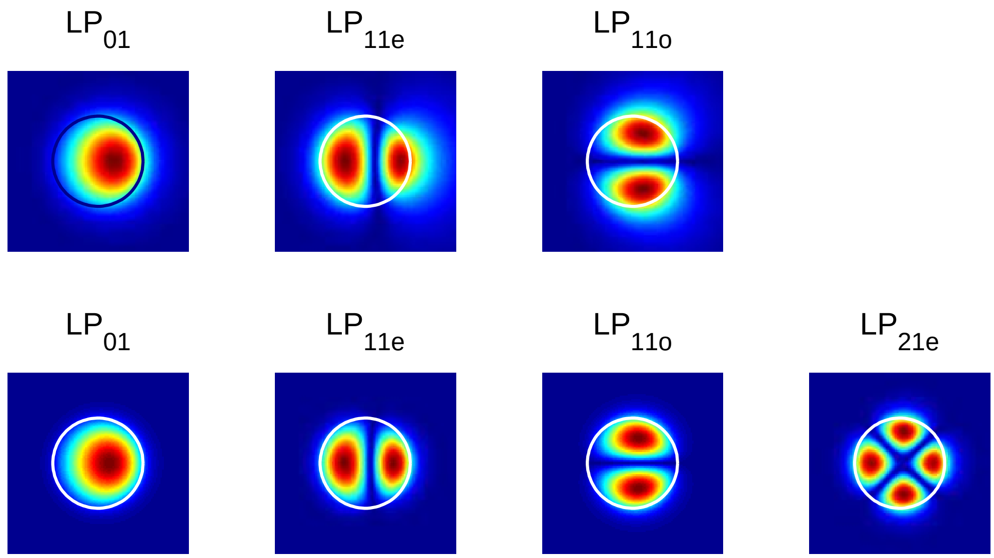


FIG. 2. Absolute magnitude of the electric field $|\mathbf{E}|$ of the mode structure for two bent fibers with $2R_{\rm co} = 20\mu$m, $R_{\rm clad} = 200\mu$m, $R = 32.2$mm and $\lambda = 1.064\mu$m. The first row represents the "guided" modes in the bent fiber with N.A. = 0.062 and the second row represents a few of the "guided" modes in the N.A. = 0.11 fiber for the same bend radius. The subscripts "e" and "o" refer to the even and odd modes with non-zero azimutal numbers, the direction for the even mode being defined in the plane of the bend (horizontal in the figure, the center of curvature being located to the left). The solid line illustrates the core-cladding boundary. The main difference between the two fibers is that the modes are much more confined to the core for the high-N.A. fiber.

structure as solved by our implemented finite difference algorithm for fibers with the same core diameter but different numerical apertures. As it can be seen on Fig. 2, the higher N.A. fiber supports more guided modes but their confinement is considerably better than for the low-N.A. fiber. An interesting element to observe is also the relationship between the LP_{01} mode in an unbent fiber and the LP_{11e} mode of the bent fiber (the subscripts "e" and "o" refer to the even and odd modes with non-zero azimutal numbers, the direction for the even mode being defined in the plane of the bend), which is non-zero because of the refractive index perturbation. The result of the overlap integral from the numerical solutions is provided on Fig. 3 (a). As we can see, the overlap integral is of substantial value in both cases but smaller for the N.A. = 0.11 fiber, which implies that the higher N.A. fiber tends to preserve modal orthogonality between the modes in the bend and the modes in the straight fiber better than its low N.A. counterpart. It is also to be noted that the overlap integral with the (bent) LP_{01} is of much higher magnitude. Furthermore, another interesting fact to notice is the difference between the effective index $n_{\rm eff}$ of the LP_{01} and LP_{11e} modes of the bent fiber, shown on Fig. 3. We can see that the difference is more important for the high-N.A. fiber. If we consider the coupling at the entrance of the bent section essentially as an instantaneous transition between fibers supporting different sets of modes, the piece of bent fiber essentially acts as a modal interferometer. In this perspective, we can define the following parameters :

$$A = \langle \mathrm{LP}_{01,\mathrm{straight}} | \mathrm{LP}_{01,\mathrm{bent}} \rangle \quad (12)$$

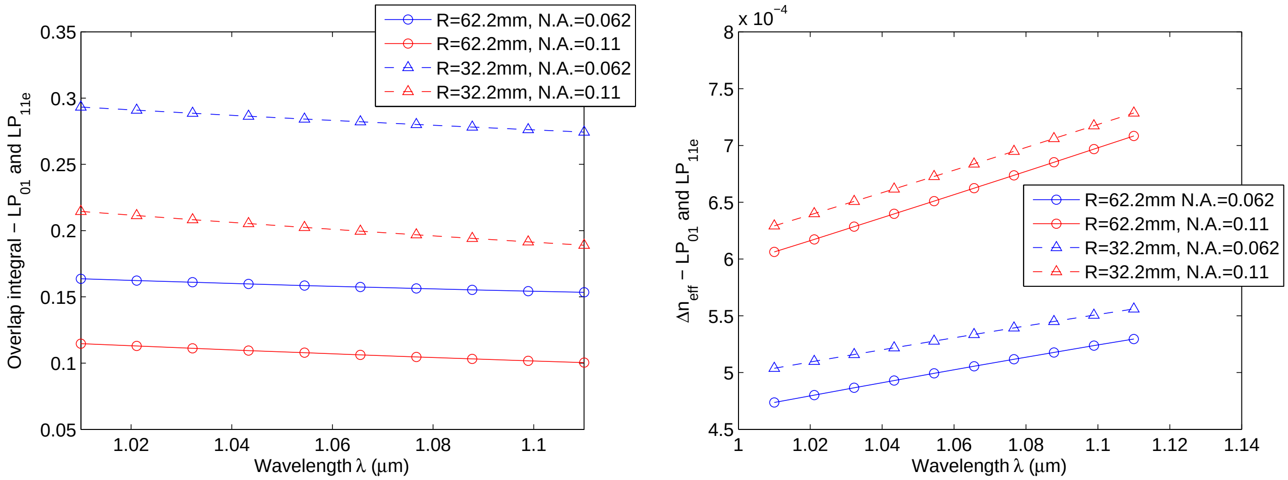
$$B = \langle \mathrm{LP}_{01,\mathrm{straight}} | \mathrm{LP}_{11e,\mathrm{bent}} \rangle \quad (13)$$

$$\Delta\beta = k \left[n_{\rm eff}(\mathrm{LP}_{01,\mathrm{bent}}) - n_{\rm eff}(\mathrm{LP}_{11e,\mathrm{bent}}) \right] \quad (14)$$

$$\langle 2\alpha \rangle = \frac{2\alpha(\mathrm{LP}_{01,\mathrm{bent}}) + 2\alpha(\mathrm{LP}_{11e,\mathrm{bent}})}{2} \quad (15)$$

Using those parameters and considering the LP_{01} transmission as a second instantaneous transition with a piece of straight fiber, the total interference can be expressed as (where A and B are the overlap integrals) :

$$T = A^4 \exp(-2\alpha_{01} L) + B^4 \exp(-2\alpha_{11e} L) + 2A^2B^2 \exp(-\langle 2\alpha \rangle L) \cos(\Delta\beta L) \quad (16)$$



(a) (b)

FIG. 3. Modal parameters in bent fibre with the same core diameter ($2R_{co} = 20\mu$m) and different numerical apertures for different bend radii. (a) Overlap integral between the (unbent) LP_{01} mode and the (bent) LP_{11e} mode ; (b) Effective index difference between the (bent) LP_{01} and LP_{11e} modes of both fibers. As we can see, the overlap integral is more important in the low-N.A. fiber and it gets larger in both fibers for smaller bend radii. This means that, for a given bend radius, modal orthogonality is better preserved in a high-N.A. fiber than in a low-N.A. fiber with the same core size.

2.3 Bend loss measurements

Bend loss measurements of two geometrically identical optical fibers ($2R_{co} = 20\mu$m and $2R_{clad} = 400\mu$m) with different N.A. have been performed. MFAs were built at each end of the fibers to ensure LP_{01} operation.[1] Detailed measurements for both fibers under study are shown on Figs. 4 and 5. Since the fiber used for the measurements was coated with a low-index polymer cladding, measurements were also performed with an index gel on a stripped section of the fiber with no significant impact on the transmitted spectrum, which rules out possible interference with cladding light as an explanation for features in the transmitted spectrum. As we can see on Fig. 6, theoretical predictions agree fairly well with experimental observations. Although the analysis of Eq. (16) does not completely explain the behavior of our low-N.A. measurement system, in particular because of the limited number of modes used and the theoretical refractive index profile taken for the simulations, it does predict some simple observation such as the position of two peaks of interference or low transmission. In this case, the period of the oscillating term is given by :

$$\Delta\beta = \frac{(2m+1)\pi}{L}, \quad m = 0, 1, 2, \ldots \tag{17}$$

which yields :

$$\lambda = \frac{2\Delta n_{\text{eff}} L}{2m+1} \tag{18}$$

In our case, we get minimum transmission in particular around $\lambda_1 \approx 1.04\mu$m and $\lambda_2 \approx 1.08\mu$m, for a fiber with $R_{co} = 10\mu$m, $R_{clad} = 10\mu$m, $R = 32.2$mm and N.A. = 0.062, which correlates with the spectrum showed on Fig. 6 (a). Also, since $L = (2l+1)\pi R$ in our experiment where $l = 0, 1, 2, \ldots$, the same extinction wavelengths should be found independently of the bending length (or number of turns), which also correlates with our data. Another important point predicted by this simple model is the change in the period of the oscillation as a function of bend radius. As shown on Fig. 3 (b), the period of the oscillating term of the transmission should decrease with decreasing bend radius R and with increasing N.A. This can be noted on the measurements done for high- and low-N.A. fibers. Also, since the overlap integral is more important in the low-N.A. fiber, the contrast of the modal interference fringes should be more important than for the high-N.A. fiber, which correlates with our observations as well.

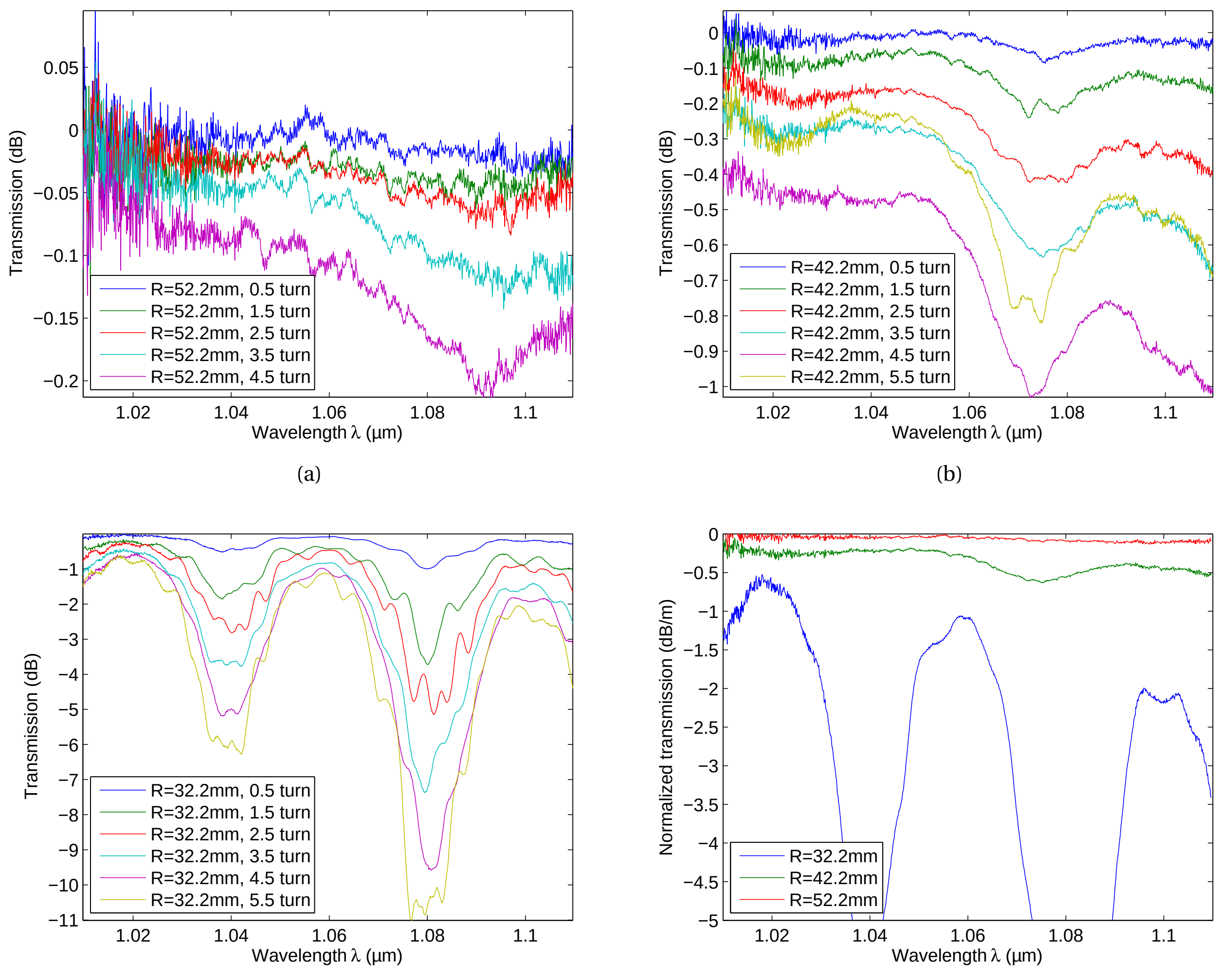


FIG. 4. LP_{01} bend loss measurements for the same optical fiber ($R_{co} = 10\mu$m, $R_{clad} = 200\mu$m, N.A. = 0.062) at different bend radius. The fiber was placed between a pair of mode field adapters or MFAs to ensure LP_{01} excitation and transmission only. (a) $R = 52.2$mm ; (b) $R = 42.2$mm ; (c) $R = 32.2$mm ; (d) Compiled loss per unit length values for all R. We can see see that a signature, similar to that of a modal interferometer is clearly present in those measurements. The contrast of the fringes, related to the overlap integral between the LP_{01} mode of the straight fiber and the LP_{11e} mode of the bent fiber is clearly greater for smaller bend radii. Also, the effective index difference Δn_{eff} gets larger with decreasing bend radius, which can be seen as a decreasing interval between fringes on the measurements as the bend radius is reduced (from (a) to (c)).

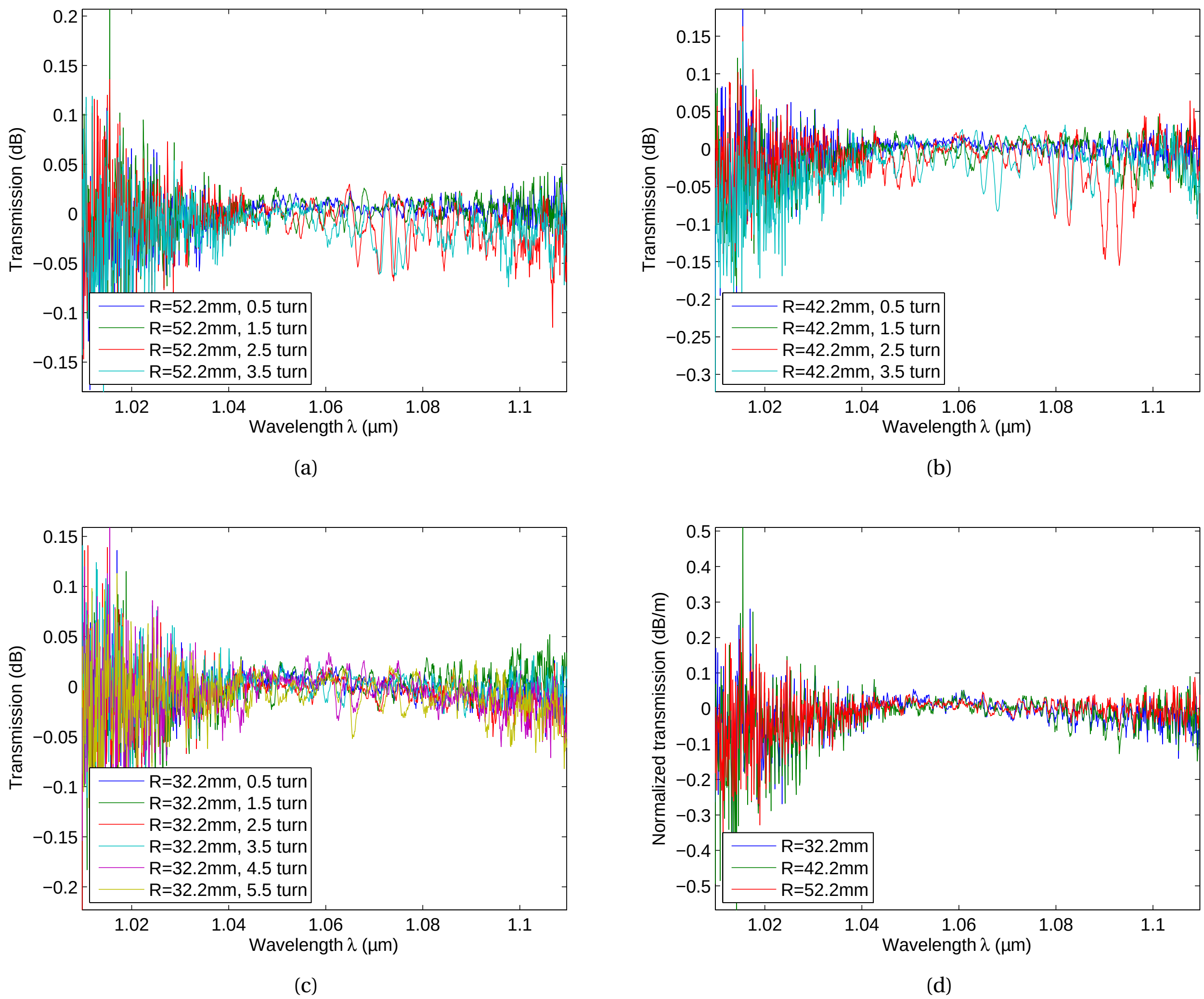
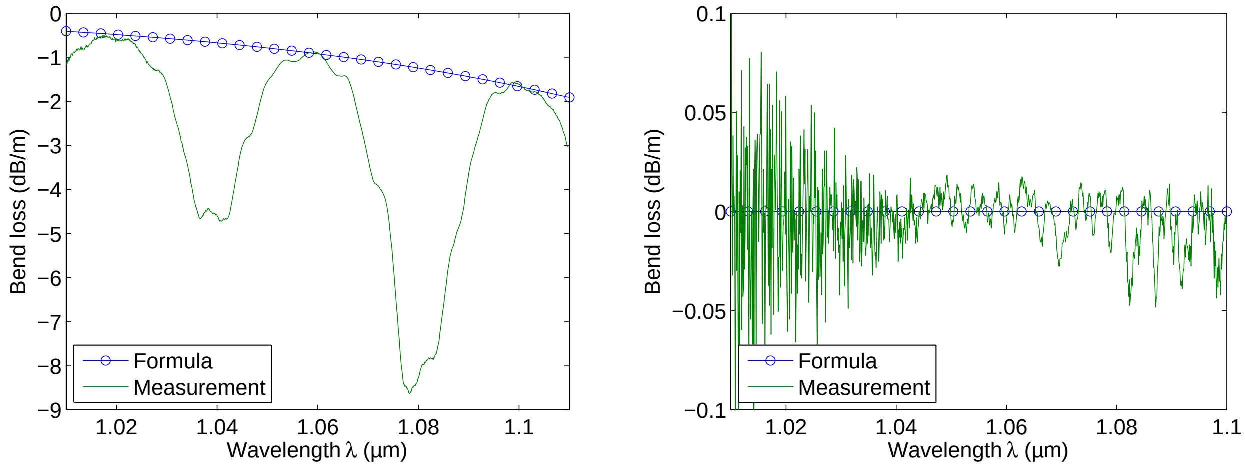


FIG. 5. LP_{01} bend loss measurements for the same optical fiber ($R_{co} = 10\mu$m, $R_{clad} = 200\mu$m, N.A. = 0.11) at different bend radius. The fiber was placed between a pair of mode field adapters or MFAs to ensure LP_{01} excitation and transmission only. (a) $R = 52.2$mm ; (b) $R = 42.2$mm ; (c) $R = 32.2$mm ; (d) Compiled loss per unit length values for all R. The noise at the edge of the spectrum is due to the low power of the source at those wavelengths. In general, we can see that the fringe contrast on those measurements is poor and that the spacing between the fringes is small, as can be expected from a modal interferometer with a large modulation frequency and a low amplitude of the oscillating term. Also note that the total loss of this fiber between two mode field adapters is very small, as it can be expected from a high-N.A. fiber where the mode is more confined to the core. Thus, conversion of LP_{01} light into higher-order modes is very small since this modal content would have appeared as loss as it is being filtered by the output MFA.



(a) (b)

FIG. 6. Bend loss measurements for different optical fibers with R_{co} = 10μm, R_{clad} = 200μm and R = 32.2mm. (a) N.A.= 0.06.; (b) N.A.= 0.11. Theoretical data calculated with the formula given by Eq. (9) using propagation constants β obtained by simulation is also included.

3. DISCUSSION

In this section, a review of the experimental results and their interpretation is performed. The issue of splicing fibers with different numerical apertures as well as a potential workaround are presented.

3.1 Bend loss - comparing fibers

Large core, low-N.A. fibers are used as relay fiber in components mostly because they provide a large effective mode area and they match the typically available gain fibers. Although a low-N.A. offers the opportunity of easily ensuring LP_{01} operation through differential gain filtering[4] (although this is subject to a careful analysis to some extent[10]), unexpected results can occur due to curvatures in systems or components using low-N.A. LMA relay fibers. Thus, mode quality and M^2 are more likely to deteriorate in low-N.A. fibers than in high-N.A. fibers provided with a good LP_{01} launch, as can be seen through the dependance of the overlap integral with the (bent) LP_{11e} to N.A. and bend radius (shown in Fig. 3 (a)). All those properties raise a certain amount of concern regarding the single mode operation of all-fiber systems containing low-N.A. LMA relay fiber in passive components, in particular in the event of its bending. Two quantities provide considerable information on bent LMA fiber operation. First, we have the effective modes width, which can be approximated by[6] :

$$W_{\text{eff},x} = \frac{R_{\text{eff}}\text{N.A.}^2(1-b_b)}{2n_{\text{co}}^2} \tag{19}$$

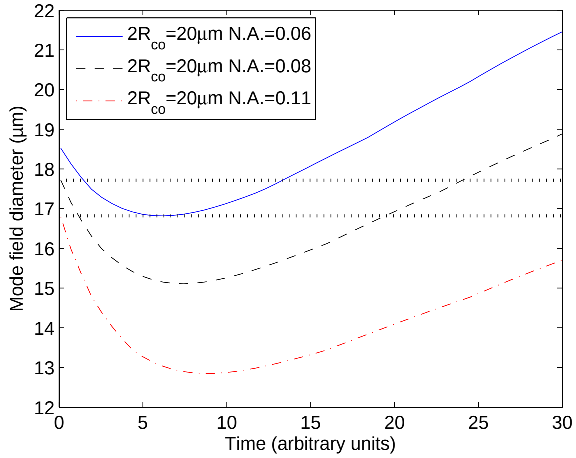
and the transition bend radius R_{trans} at which the modes become whispering gallery modes[6] :

$$R_{\text{trans}} = \frac{2R_{\text{co}}}{1-b_s}\left(\frac{n_{\text{co}}}{\text{N.A.}}\right)^2 \tag{20}$$

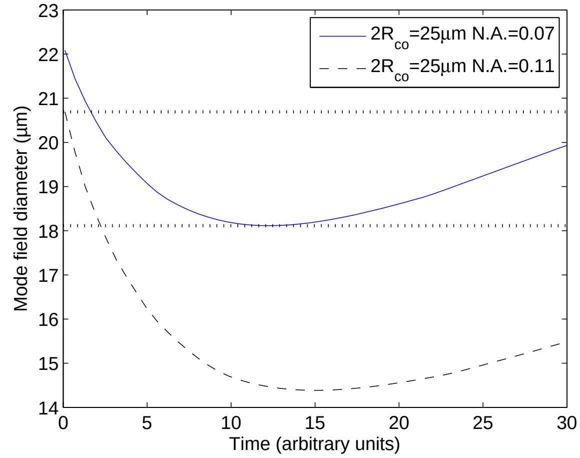
or, in terms of the normalized parameter $\mathfrak{R}$[6] :

$$\mathfrak{R}_{\text{trans}} \equiv \frac{2V}{1-b_s} \tag{21}$$

which, interestingly, depends only on the parameters of the straight fiber. Thus, in addition to its tendency to inhibit mode coupling in the bent fiber, a higher N.A. fibers both reduces the transition bend radius, at which loss becomes significant, and reduces the change in effective width of the mode. Strangely, this means that increasing the N.A. both reduces bend loss and preserves modal area, thus reducing the increase of the maximum field amplitude (causing nonlinear effects) due to bending.[11] Additionally, increasing the N.A. of an LMA fiber tends to make it more stable in terms of modal content. Also, for a given N.A., another way of stabilizing the transmission is to use higher-order modes, which will both reduce the values of b_s and b_b.[12]



(a)



(b)

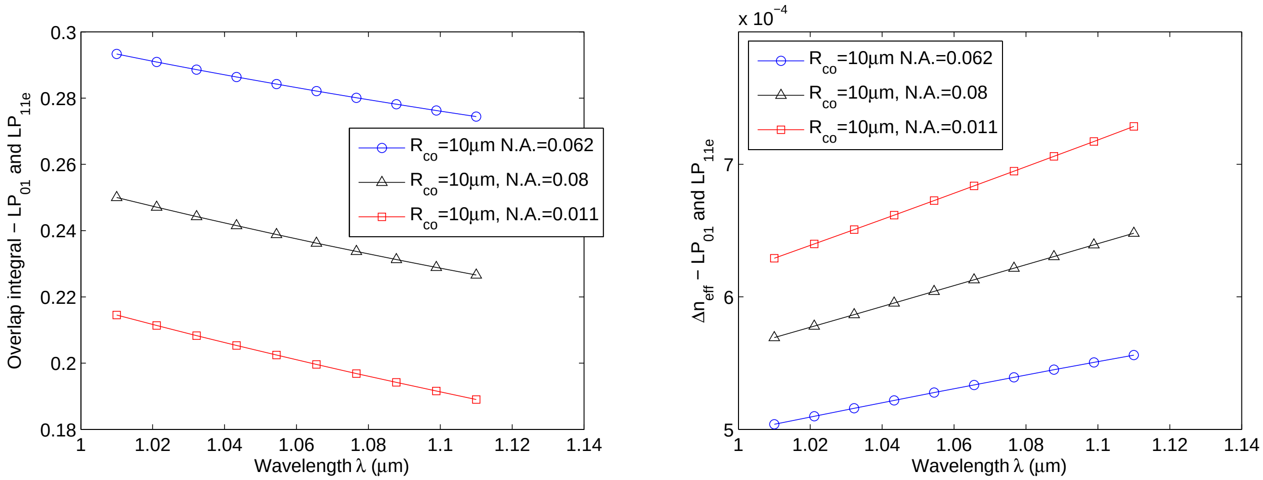
FIG. 7. Illustration of mode field diameter (MFD) matching using the MFA technology for a splice between fibers with different N.A. (a) Fibers with $2R_{co} = 20\mu$m and N.A. = 0.06, 0.08 and 0.11 ; (b) Fibers with $2R_{co} = 25\mu$m and N.A. = 0.07 and 0.11. We notice that it is possible to match the MFD of geometrically identical fibers with different N.A. since the curves share a common set of values between the two dotted ($\cdots$) lines on both graphs, except for the $2R_{co} = 20\mu$m, N.A. = 0.11 fiber which can't be matched with its N.A. = 0.06 counterpart. Although a fiber with the same core radius but with N.A. = 0.11 would be even more stable, a splice between the 20μm core N.A. = 0.11 and N.A. = 0.06 fibers would be difficult since no overlap exists between their MFD range. The MFD overlap range is defined before the minimum of the curve since the goal is to achieve a mode match with a quick splice to minimize diffusion. Beyond the minimum, diffusion becomes important. Splices between $2R_{co} = 25\mu$m N.A. = 0.07 gain fiber and matching N.A. = 0.11 relay fiber have been performed with LP_{01} loss around 0.5dB. Both of these figures thus suggest that there is a parameter space that allows matching two dissimilar fibers together that depends both on the N.A. increase and core dimensions.

3.2 Splicing N.A.-mismatched fibers

Most of the time, splicing fibers in LMA systems proves to be a tedious task of critical importance, especially in terms of loss and conservation of the modal content. This paper suggests that a system could be built using coiled, low-N.A. gain fiber and a higher N.A., more stable relay fiber. As we can see in Fig. 7 (a) and (b), a good match can in theory be performed between fibers with the same core diameter but slightly different N.A. by use of the MFA technology,[1] although it depends both on the core diameter and the value of the N.A. of both fibers. Fig. 7 (b) shows a match for two 25μm core fibers with considerably different N.A. (0.07 and 0.11). Such a match has been made experimentally with LP_{01} loss in the range of 0.5dB. On the other hand, Fig. 7 (a) suggests that such a high increase in N.A. (from 0.06 to 0.11) cannot as easily be performed for a fiber with a slightly smaller core diameter (20μm). Thus, an intermediate solution consisting of a relay fiber with a 20μm core diameter and N.A. = 0.08 is possible. Using Eq. (20), we can perform an analysis of the bending robustness of the high-N.A. fiber relative to that of the low-N.A. gain fiber :

$$\frac{R_{\text{trans},0.062} - R_{\text{trans},0.08}}{R_{\text{trans},0.062}} \approx 0.10 \tag{22}$$

which represents an enhancement in the resistance to bends of 10% of the R_{trans} value of the N.A. = 0.062 gain fiber. This is considerable, taking into account the slight change in MFD and, consequently, maximum field amplitude. The increase in maximum field value is of about 6.24% from one fiber to the other, which is of the same order of magnitude than the increase in maximum field value due to bending, which is estimated from the simulations to be 5.74% for a bend radius of $R = 32.2$mm. Also, both the beat frequency between the modes ($\Delta\beta$) and the overlap integral between the LP_{01} and the (bent) LP_{11e} modes (seen on Fig. 8) ensure a more stable net LP_{01} transmission. Thus, splicing fibers with slightly different N.A. is possible, at a very low cost on MFD variation but tremendous gain on net LP_{01} transmission and stability in the relay fiber. It is thus conceivable to make a system with slightly different fibers to allow considerably more stable single-mode operation. Although only changes in N.A. were considered in this analysis, slight changes in the core radius are also possible but subject to a robustness analysis through Eq. (20) to ensure that the fiber is indeed



(a) (b)

FIG. 8. Modal parameters in bent fibers with the same core diameter ($2R_{co} = 20\mu$m), different numerical apertures and the same bend radius R = 32.2mm. (a) Overlap integral between the (unbent) LP_{01} mode and the (bent) LP_{11e} mode; (b) Effective index difference between the (bent) LP_{01} and LP_{11e} modes. As we can see, as the N.A. increases, the fiber is more stable. In addition to being a sturdier solution for the relay fiber, the N.A. = 0.08 fiber can also be spliced to an N.A. = 0.06 gain fiber, as shown in Fig. 7.

more stable. We need to note though that R_{trans} tends to increase with increasing values of R_{co} which makes it a slightly less preferable choice than increasing the N.A. when it comes to increasing modal stability in the fiber (decreasing R_{trans}).

3.3 Notes on fiber resistance to bends as a function of external cladding dimensions

Another important aspect to be taken into account when evaluating the stability of a fiber is its natural resistance to bending for a given set of external forces, regardless of their origin. Bending in a fiber is ultimately a response to an externally applied torque τ. The radius of curvature R of a fiber can be expressed, in terms of fiber geometry and applied torque, as follows[13] :

$$R = \frac{\pi E R_{clad}^4}{4\tau} \tag{23}$$

where E is the fiber Young's modulus and R_{clad} is the cladding radius. Thus, the radius of curvature of a fiber is very sensitive to the cladding dimensions of the fiber, much more in fact than it is to the applied torque. This means that, depending on the type of application and the power levels, increasing the cladding diameter of the fiber can prove to be an efficient way of making the system less sensitive to external forces. This increase in stability, however, may result in a poorer pump absorption rate for conventional double-clad fiber geometries since the absorption rate decreases monotonically with increasing cladding diameter.

4. CONCLUSION

In this paper, we have illustrated, both theoretically and experimentally, that, with a proper LP_{01} excitation, higher N.A. fiber tend to preserve the modal content better and create less loss than low-N.A. LMA-fibers. Thus, higher N.A. fibers are less sensitive to bending caused by the manufacturing process of components or assemblies when it comes to preservation of the modal content. Although high N.A. fibers do support more modes, a good LP_{01} launch in the fiber can thus greatly improve the fundamental mode transmission of the complete system. This can be achieved, for example, with the use of a single mode seed and a mode field adapter (MFA)[1] or integrated MFA combiners. In the same manner, for unseeded systems using low-N.A. gain fiber, splices with higher N.A. relay fibers can potentially be performed with very low loss (<0.5 dB) wih the MFA technology.

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