SINGLE-MODE FIBER LENGTH FOR WAVEFRONT FILTERING

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Abstract: Stellar nulling interferometry offers the possibility of direct imaging of extrasolar planets necessary for the detection of extra-terrestrial life. Achieving optimum performance from the interferometers requires that the wavefronts of light reaching the interferometer are free of distortions. This is achieved by using single-mode fibers, which are excellent wavefront filters. In this paper, we present an improved theoretical model to estimate the minimum fiber length required to achieve a certain degree of filtering and show that the effects of both the fiber characteristics and launching conditions of the input optical field should be considered to determine the minimum length.

1. INTRODUCTION

The search for extra-terrestrial life outside our solar system has attracted much recent attention resulting in the launch of projects such as the DARWIN mission by the European Space Agency [1] and the Terrestrial Planet Finder (TPF) mission by the National Aeronautics and Space Administration (NASA) [2]. The key idea within DARWIN and TPF is to collect the light emitted by candidate planets and perform spectroscopic analysis to detect signs of life-supporting elements and compounds. The planets emit more strongly in the infrared wavelength range as compared to the visible wavelengths. Still, the light emitted by the planet in the infrared is typically a million times weaker than the light emitted by the star. Consequently, the faint signal from the planet has to be filtered out from the much brighter emission of the parent star to perform the spectroscopic studies. Bracewell and MacPhie first suggested using nulling interferometry to suppress the starlight [3][4]; so called because the interferometer is based on suppressing the starlight by pointing a null in the interference fringe pattern on the star. Detection of Earth-sized planets requires that the unwanted starlight should be suppressed by almost 60dB relative to the intensity of light emitted by the planet [1]. This can be achieved with existing optical instrumentation capabilities only if the wavefronts reaching the interferometer arms are free of any distortions, thereby necessitating wavefront filtering. Single-mode optical fibers are ideal wavefront filters because they can rectify a wide range of spatial frequencies and optical aberrations with minimal loss of photon flux over a wide range of wavelengths [5].

The single-mode fibers used as the wavefront filters typically consist of a core and cladding that is surrounded by an absorption coating for achieving maximal suppression of the cladding modes [6], [7] . Ideally, the spatial distribution of a single-mode fiber output is independent of the input launching conditions. However, in practice, the input field excites thousands of higher order (cladding) modes (HOMs) as well as the fundamental mode (FM) of the fiber. Thus, a certain fraction of the output power always remains in the cladding modes, which ultimately limit its filtering performance. The absorption coating on the fiber is designed to improve its filtering capability by increasing the propagation loss of the unwanted cladding modes. Thus, longer lengths of fiber have a lower fraction of power in the cladding modes and hence, are better wavefront filters. However, in order to minimize the complexities associated with deployment in space, like vibration, bends etc., the minimum possible lengths (~ few centimeters) of fiber that can provide truly single-mode output, need to be used. This makes it crucial to correctly estimate the minimum fiber length and much research has focused on developing theoretical models to estimate the minimum fiber length needed to achieve the -60dB suppression of higher order modes [6], [8], [9]. In this paper, we show that prior models [6], [8] that are based on the effects of fiber design alone are over-simplified for application to the realistic fibers used for wavefront filtering. We present an improved model that provides a better estimate of the filter length by incorporating the effect of both the fiber characteristics and the input launching conditions.

1.1 Efficiency of a wavefront filter

The efficiency of a wavefront filter is proportional to its capability to reject any light signal other than the FM. It is measured in terms of the ratio of power in the FM to the power in all the other HOMs at the output [6], and is defined in terms of the parameter R (rejection ratio) defined as follows:

$$R(L) = \frac{P_{FM}\,(z = L)}{P_{HOM}\,(z = L)} \tag{1}$$

where P_{FM} and P_{HOM} is the power in the FM and HOMs, respectively, at the output end of the fiber. Propagation is assumed along the z-direction and L is the length of the fiber.

Previously reported models [12,15] considered the worst case scenario by assuming that the fraction of input power that is not coupled into the FM gets coupled into the HOM having the lowest loss, which is the LP_{11} mode in the case of a step-index fiber with an infinitely extended cladding, yielding the following expression for R (using Eq.1)

$$R = \frac{\eta_0 e^{-\alpha_0 L}}{(1-\eta_0)e^{-\alpha_1 L}} \quad (2)$$

where η_0 and α_0 is the coupling efficiency and confinement loss of the FM, and α_1 is the confinement loss of the LP_{11} mode of the fiber.

However, in practice, the fibers have a finite cladding that is surrounded by an absorption coating that may be a high-index material, like chromium [7]. The finite cladding supports numerous cladding modes and the LP_{11} mode does not necessarily have the lowest loss in such structures. Moreover, the fraction of input power coupled into a particular HOM depends critically on the launching conditions and symmetry of the modes. Even if a particular cladding mode has very low loss, it may not be a dominant factor in deciding the filter length if its coupling efficiency is negligible.

2. PROPOSED MODEL

In stellar interferometry, the fiber is usually placed in the focal plane of the telescope [10]. The field exiting the telescope is in the form of an Airy disk and is fed into the single-mode fiber for wavefront filtering. The size of the Airy disk (field) is optimized to ensure optimal coupling into the single-mode fiber. Accordingly, in the simulations presented here, we assume the input field is an Airy disk that provides maximum overlap (~ 78%) with the FM of the fiber, at the operating wavelength.

The power coupling efficiency (η) of the input field launched into a particular mode of an optical fiber (neglecting the effect of Fresnel reflections at the fiber facets) is proportional to its overlap integral, and is defined as [11]

$$\eta = \frac{\left| \iint_A E_{in}^* E_{op}\, dxdy \right|^2}{\iint_A \left|E_{in}\right|^2 dxdy \iint_A \left|E_{op}\right|^2 dxdy} \quad (3)$$

where E_{in} is the complex input field and E_{op} is the optical mode of the fiber. A is the fiber area on the $X-Y$ plane transverse to the optical axis. In the proposed model, we first calculate the confinement loss and power coupling efficiencies of the FM as well as a large number (≈ 300) of fiber cladding modes. The complex effective indices of the fiber modes are obtained by solving the full-vectorial Maxwell differential equations using the finite-element method (with the commercial software, COMSOL®). The imaginary parts of the effective indices are proportional to the confinement loss of the modes. Let η_i and α_i be the coupling efficiency and confinement loss of the i^{th} cladding mode, respectively. If we neglect inter-modal scattering, the fraction of power remaining in the various HOMs after a certain fiber length would depend on the coupling efficiency of the modes at the input and their propagation loss. This is elaborated in Fig.1, which is a schematic representation of the power carried by the various modes propagating along a fiber

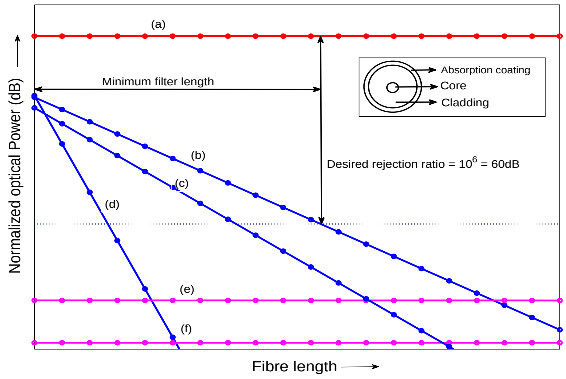

Fig.1. Schematic representation of modal power along fibre length (a) FM (b-d) Modes whose overlap with input field > 1% (e,f) HOMs exhibiting very low confinement losses. Inset: Cross-section of the fibre structure

The input field is an Airy disk and the power in each mode at the input is normalized with respect to its coupling efficiency. It can readily be seen that even though modes (e,f) exhibiting loss comparable with the fundamental mode exist, they would carry a negligible fraction of the power for practical excitation conditions. Thus, modes (b,c,d) that have higher overlap with the input field are likely to be more important even though their propagation loss are higher than modes (e,f). As the required degree of filtering increases, however, at longer fiber lengths, the effect of low-loss modes begins to become more significant.

2.1. Modal analysis

In the proposed model, we assume that the fraction of power that does not get coupled into the FM (i.e. $1-\eta_0$) is distributed amongst only those cladding modes that have coupling efficiency greater than a certain threshold, for e.g. 0.1% of the input field. The fractional power coupled into these modes is assumed to be proportional to their overlap with the FM. Since the total power is constant, the coupling efficiency (η_i') of these cladding modes is modified as follows:

$$\sum_{i=1}^{N} \eta_i' = a * \sum_{i=1}^{N} \eta_i = 1 - \eta_0 \quad (4)$$

where a is the constant of proportionality and N is the number of modes that have coupling efficiency greater than the threshold value. Eq.4 shows that a cladding mode having a higher overlap with the input field will account for a higher fraction of power in the cladding at the fiber input. Using Eq.1, $R(L)$ is now defined as

$$R(L) = \frac{\eta_0 e^{-\alpha_0 L}}{\sum_{i=1}^{N} \eta_i^{'} e^{-\alpha_i L}} \quad (5)$$

Eq.5 is numerically solved to obtain an estimate of the minimum fiber length (L) required to achieve the desired value of R. It is important to note that we have ignored inter-modal scattering effects and inter-modal power transfer in this analysis, which is potentially an issue in practice.

3. RESULTS AND DISCUSSION

The fiber studied in this paper is a silver halide fiber reported in Ref.[8]. It has a core radius of 25µm and cladding radius of 350µm. A 100µm thick absorption coating (index-matched to the cladding) was deposited on the cladding, which exhibited a loss of ~ 500dB/m at infrared wavelengths. The numerical aperture of the fiber was 0.14 at 10.6µm wavelength and its cut-off wavelength was 9.14µm. The cladding of the fiber supports numerous unwanted radiation modes. Fortunately, simulations showed that most of these modes exhibit very high propagation loss (>200dB/m) and are lost within a few centimetres of propagation in the fiber. Among the modes that have losses less than 200dB/m, the fiber supported 12 cladding modes that had coupling efficiency > 0.1% and are of interest according to the proposed model. Figure 3(a) shows that the intensity distribution of the launch field (Airy disk) and Fig.3(b) shows the FM excited in the fiber, which is well-confined within the central core at 10.6µm. Substituting the loss and coupling efficiency values of the cladding modes with η>0.1% into Eq.5 yields a minimum fiber length of ~ 48cm for

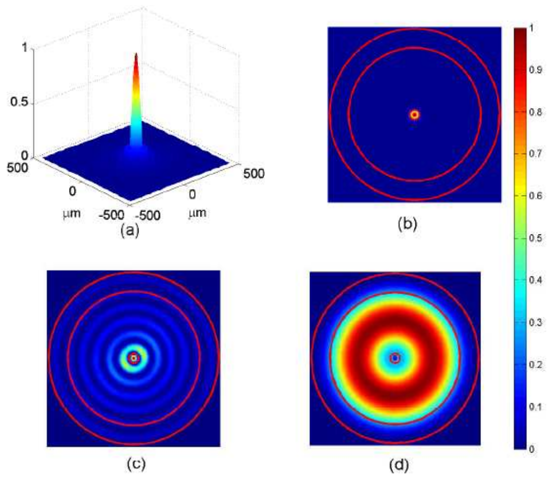

Fig. 2. Transverse intensity profile of (a) input field (Airy disk) (b) FM (c) cladding mode with highest coupling efficiency (≈ 1.28%) (d) LP_{11} mode, overlap with Airy disk is zero. The solid red lines represent the fiber geometry.

achieving R = 60dB. This length is strongly influenced by the lowest loss (~ 105dB/m) that is exhibited amongst these modes. We also observe that most of these cladding modes have intensity maxima at the centre of the fiber, which manifests in the relatively large value of the level of excitation. Fig.3(c) shows the transverse intensity profile of the mode that has the highest coupling efficiency with the input field. In comparison to the proposed method, the previously reported model [6] (Eq.2) yields a filter length of almost ~ 160cm to achieve the same value of R. It is also important to note that the loss of the LP_{11} mode (~ 41dB/m, transverse intensity profile shown in Fig.3(d)) is not the lowest loss exhibited among all the cladding modes. Moreover, its coupling efficiency with the input field is theoretically zero since it is an anti-symmetric mode while the Airy disk is a symmetric field. The lowest loss exhibited amongst all the cladding modes is ~ 33 dB/m. However, the coupling efficiency of the mode is less than 0.1%. Thus, if we consider modes with coupling efficiency > 0.1%, both the LP_{11} mode and the lowest loss mode are not involved in the model for estimating the minimum filter length.

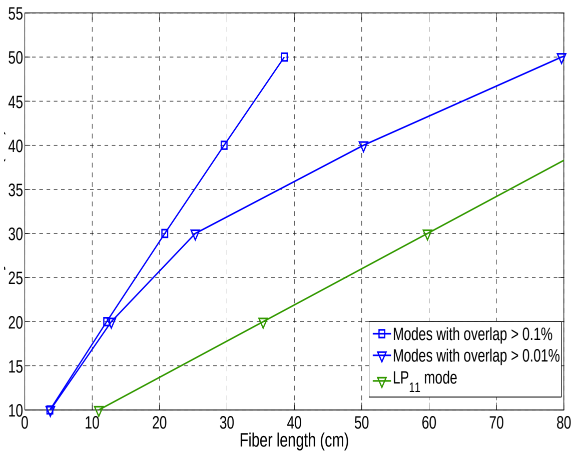

Fig. 3. Comparison of minimum fiber length calculated by the proposed model and model proposed in Ref.[6]

In Fig. 3, we have plotted the filter lengths obtained by considering a finite number of cladding modes whose coupling efficiency with the input field is greater than 0.01% and 0.1%. For comparison purposes, we have also shown the filter length predicted by the previously reported model that considers the LP_{11} mode alone [6]. We observe that the results obtained by the proposed method for η > 0.1% and η > 0.01% are in good agreement with each other for R up to 40dB. The fact that the minimum fiber length is independent of the threshold we set on the overlap of the modes with the input field justifies our assumption that we can approximate the total power distribution and propagation of all the cladding modes of the fiber by considering the propagation of a finite number of cladding modes that have the highest overlap with the input field. However, we do note that the estimated results do not compare very well for R > 40dB. This can be attributed to the fact that for R > 40dB, the cladding modes that have coupling efficiency less than < 0.1% along with low loss become significant, and these need to be considered to obtain a correct estimate of the filter length. The linear behaviour of the curves for R > 40dB (in Fig. 3) corresponding to the cladding modes that have η>0.01% and 0.1% suggest that the curve is dominated by the loss of one/few such mode(s). A further study revealed that the slope of the curve for η>0.01% corresponds to the loss of the mode that exhibited the lowest loss of 33dB/m and had a coupling efficiency of just 0.09%. This mode is excluded from the model when we considered modes with coupling efficiency > 0.1%. The strong influence of this mode on the filter length illustrates that for long fiber lengths, the modes that have the lowest losses along with a finite coupling efficiency ultimately determine the filtering capability of the fiber. Thus, higher the value of R involved, the lower the threshold of the overlap that needs to be considered (for Eq.4) in order to obtain a correct estimate of the filter length.

4. CONCLUSION

We have presented a theoretical model to estimate the minimum length of a single-mode fiber required to achieve a desired degree of higher-order mode filtering. The proposed model can be applied to study any arbitrary fiber geometry and provides a more accurate estimate of the minimum filter length than the previously reported models based on considering the loss of the LP_{11} mode alone. It is especially useful for studying fibers that have high-index metal coatings as the absorption layer, which cannot be analyzed with other numerical techniques such as the beam propagation method. We show that by considering the loss as well as the coupling efficiency of the cladding modes, we can identify a finite number of cladding modes that can yield a good estimate of the minimum filter length. The proposed method helps to identify the impact of the launching conditions on the filtering performance of the fiber. Simulations indicate that under ideal launching conditions (Airy disk); the symmetric cladding modes that have intensity maxima at the centre of the fiber ultimately determine the filter length. However, it should be noted that the errors in the estimated length can be significant for cases where R > 40dB. In such cases, a large number of modes should be considered in order to minimize the inaccuracy. The results suggest that the excitation/ launching conditions are crucial in achieving optimum performance of the wavefront filter in a practical setup.

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