Measurement of spatial filtering capabilities of single mode infrared fibers

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Abstract
Spatial filtering is necessary to achieve deep nulls in optical interferometer and single mode infrared fibers can serve as spatial filters. The filtering function is based on the ability of these devices to perform the mode-cleaning function: only the component of the input field that is coupled to the single bound (fundamental) mode of the device propagates to the output without substantial loss. In practical fiber devices, there are leakage channels that cause light not coupled into the fundamental mode to propagate to the output. These include propagation through the fiber cladding and by means of a leaky mode. We propose a technique for measuring the magnitude of this leakage and apply it to infrared fibers made at the Naval Research Laboratory and at Tel Aviv University.

Introduction
Direct observation of Earth-like extrasolar planets with regular telescopes is impeded by the bright star, whose light overwhelms the faint image of a planet orbiting around it. The use of interferometers for planet finding relies on suppressing the star light by combining beams from two telescopes out of phase. One of the impediments to this technique is the existence of wavefront errors in the telescopes - the wavefronts originating from the two telescope mirrors may not have the exact same shape, so the difference between the wavefronts will cause residual signal at the null.

Spatial filters can help achieve deep nulls by equalizing the wavefronts. The use of single mode optical fibers for spatial filtering has been discussed previously\(^1\). A step-index fiber consists of a high index cylindrical core and low index cylindrical cladding that encloses the core. Single mode fibers have only a single bound mode, therefore only the component of the input field that couples into this fundamental mode of the fiber will propagate to the output without loss. An ideal modal filter would have only this component of the input field reaching the output. However, in practical devices, other components of the input field may also appear at the output. (1) Some components of the input field can couple into leaky modes which carry the energy to the output with little loss. Leaky modes were considered in detail by Snyder and Love\(^2\) and Sammut and Snyder\(^3\). (2) The energy can also be carried through the cladding of the fiber. The cladding itself acts as a light pipe that very effectively captures the light not coupled into the bound or leaky modes, as well as the light radiated from the core by leaky modes. Typically, the outside of the cladding is covered with light-absorbing material to reduce light propagation through the cladding.

Previously, the following techniques have been used to ascertain the single mode operation of the fiber. One method is to construct an interferometer and measure its null depth with and without the mode-filtering fiber. This provides confirmation of single
mode operation if the null depth improves greatly, but does not help in troubleshooting the fiber if not enough improvement is observed. Shalem et al.\textsuperscript{4,5} have demonstrated a near field scanning technique whereby an IR fiber with a sharp end is scanned along the output end of the fiber. It has been shown to detect multiple bound modes in IR fibers. Techniques utilizing far field pattern analysis have also been used, in which a “nice” single peak pattern, sometimes fit to a Gaussian, is taken as a sign of single mode operation.

A drawback of the abovementioned techniques when applied to a fiber with very few bound modes is that one may be able to carefully match the input beam to the fiber so that the coupling to the fundamental mode dominates. If this is the case, the fiber output – both in near and far fields - will reflect only characteristics of the fundamental mode. In addition, IR fiber ends can not be polished with the same ease and precision as communication fibers due to the use of much softer materials. The resulting imperfect fiber end may spoil the otherwise perfect far field pattern of a single mode fiber leading to its misidentification as a multimode device.

A useful variation on the far field technique was implemented by K. Nakajima et al.\textsuperscript{6} They compared the width of the far field pattern for different illumination conditions, such as different position of the input spot. Shifting the input spot over the input end of the fiber changes the distribution of launched power between the fiber modes and will, if multiple bound or weakly evanescent leaky modes are present, alter the power distribution between them. This change is bound to show up in the far field pattern.

**Measurement setup**

Our technique extends the idea of Nakajima et al.\textsuperscript{6}: rather than varying the amount of light coupled into higher order modes, we illuminated the fiber with the field that is not supposed to couple into the fundamental mode at all. For a cylindrical single mode fiber any anti-symmetric field aligned with the center of the fundamental mode will fit the bill. With such input, the intensity at the output could be due to two processes: (1) the light propagation through the core by means of higher order bound or leaky modes, or (2) the light propagation through the cladding. In the latter case the light may initially either couple to leaky modes and then radiate into the cladding, or couple directly to the cladding.

Our experimental setup is depicted in Figure 1. As depicted in Fig. 1A, a collimated beam from an illuminator is reflected off a mirror with a step in the middle which introduces a phase shift between the two halves of the reflected beam. The incidence angle was adjusted so that the phase difference at the source wavelength was equal to \(\pi\). Therefore, the field distribution in the focal spot was anti-symmetric as schematically shown in Fig. 1D. This wavefront phase shifting technique is conceptually similar to the one implemented in Ref. 7. Initial experiments were performed using collimated light from a quantum cascade laser (QCL) emitting at 10.5 \(\mu\)m wavelength - depicted in Fig. 1B as “illuminator #1”. Once we had identified fibers with single mode behavior, we started using one of them in the illuminator setup for mode cleaning - depicted in Fig. 1C as “illuminator #2”.

Figure 1. (A) through (C): Experimental setup for measuring non-fundamental mode transmission in single mode fiber. (D) Field distribution at the fiber input (illustration).

The stepped mirror was fabricated as follows. We started with a regular 3” round mirror, and spun AZ 5214 photoresist onto its front surface at 1000 rpm for 40 s. The resist was then baked in an oven. Next, one half of the surface was exposed to UV light and then developed in AZ 400K developer thereby forming a 2.42±0.03 μm step as measured using a profilometer. The surface was then coated with an 800 A layer of gold, using electron beam evaporation.

**Results and discussion**

We report results of measurements on two fibers. Fiber #1 was produced by the Naval Research Laboratory (NRL) and was made of chalcogenide glass; fiber #2 was made of polycrystalline silver halide materials produced by Tel Aviv University (TAU). The design parameters of these fibers are presented in Table 1. As can be seen, the waveguide parameter $V$ for both fibers is below the critical value $V_c$ of 2.405 (for 10.5 μm), above which the fiber becomes multimode.

We measured the far field pattern of fiber #1 and discovered it has a smooth single peak shape and displays NA of 0.22±0.3, which is consistent with the design parameters. The far field pattern of fiber #2 was not measured because the input conditions of the current setup were unfavorable for the lower numerical aperture of this fiber leading to low signal-to-noise ratio.
For both fibers, we scanned the fiber tip along the focal plane using an X-Y stage to characterize the coupling of the anti-symmetric field into it. The 3D graphs of the output intensity distribution vs. fiber position are shown in Figs. 2A and 2B for fibers #1 and #2 respectively. The cross sections through the center of the two peaks are shown in figures 3A and 3B.

Table 1. Design parameters of tested infrared fibers. Fiber #2 has two claddings.

<table>
<thead>
<tr>
<th></th>
<th>Length (cm)</th>
<th>Core Diameter (µm)</th>
<th>Cladding 1 Diameter (µm)</th>
<th>Cladding 2 Diameter (µm)</th>
<th>Waveguide parameter $\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber #1</td>
<td>20</td>
<td>23</td>
<td>2.725 N/A</td>
<td>127 2.714</td>
<td>1.66</td>
</tr>
<tr>
<td>Fiber #2</td>
<td>50</td>
<td>50</td>
<td>2.13 350 2.1245</td>
<td>900 2.147</td>
<td>2.27</td>
</tr>
</tbody>
</table>

Figure 2. Fiber output intensity vs. fiber tip position in the focal plane. The measurement setup is depicted in Figure 1.

The output intensity profiles shown in Figs. 2 and 3 fulfill our expectations for single mode fibers. The minimum between the two peaks occurs when the node of the input field aligns with the center of the fundamental mode of the fiber. The signal magnitude at this point is not exactly zero due to the small leakage of light through the mechanisms described above. Ideally, when the intensity is at minimum between the two peaks, the input field does not couple to the fundamental mode and the output is entirely due to the leakage. The peaks in these profiles occur when the fundamental mode of the fiber is positioned at the maximum or the minimum of the input field shown in Fig. 1D; in these positions the contribution of the light propagating via the fundamental mode is
predominant. For small leakage, except near the center between the two maxima, the coupled power $P_{c0}$ can be expressed as

$$P_{c0}(x, y) \approx P_B \left| \int_{A_0} E_0(x-x', y-y') F^*(x', y') dA \right|^2,$$

where $P_B$ is the power in the input beam, $E_0$ is the normalized fundamental mode of the fiber and $F(x,y)$ in the normalized input field distribution. The output power measured by the detector is $P_{out0}(x,y) = P_{c0}(x,y) \Gamma_0$ where $\Gamma_0$ is the power attenuation factor for the fundamental mode.

(1) Propagation by means of a leaky mode.

While a single mode fiber has multiple leaky modes, the power attenuation rises quickly for higher order modes, so propagation through the lowest order leaky mode should dominate. To get an order-of-magnitude estimate of the attenuation of the least attenuating leaky mode in both fibers, we have used the analytical approximation given in Ref. 2. We found the attenuation in fiber #1 of $-6000$ dB and in fiber #2 $-900$ dB. Given the sensitivity of our detection system, we should not be able to see any signal at the output. Nevertheless, to demonstrate the proposed technique, it is worthwhile to proceed investigating this mechanism, especially in fiber #2 which is designed quite close to the cutoff, so that small variations in the core or cladding refractive indexes may lead to an observable signal.

We can find $P_{cl}$, the power coupled into the least attenuated leaky mode using the expression
\[ P_{cl}(x, y) = P_0 \left| \int_{A} E_L(x - x', y - y') F^*(x', y') \, dA \right|^2 , \]  

(2)

where \( P_{cl} \) is the power coupled into the leaky mode and \( E_L \) is the modal field for this mode. This modal field is normalized over the area \( A \), bound by a circle of turning point radius \( r \) as defined in Ref. 3. We are interested in the lowest point between the two peaks \((x_{\text{min}}, y_{\text{min}})\) where the coupling into the fundamental mode disappears and leakage dominates the output power. At this point the detected power is \( P_{cl}(x_{\text{min}}, y_{\text{min}}) \Gamma_L \), where \( \Gamma_L \) is the power attenuation of the leaky mode.

In order to find the overlap integral in Equation (2) we need to evaluate the modal field \( E_L \) and the input field \( F \). We have used Photon Design software to compute the lowest order leaky mode in fiber #2. The input field \( F \) was computed from the experimental measurement by taking a square root of measured power and applying deconvolution to the result, as suggested by Equation (1). Since the central part between the two maxima is dominated by leakage so that Equation (1) is not valid, we have forced the central minimum of \( P_{cl}(x, y) \) to zero and extrapolated several data points around it. Due to rather wide spread of the leaky mode field \( E_L \), the number of extrapolated points at the center had very little effect on the value of the overlap integral.

The resulting attenuation factor \( \Gamma_L \) is ~0.05\( \Gamma_0 \); the expected value of \( \Gamma_0 \) is greater than 0.3 (similar fibers produced at TAU, have losses less than 20 dB/m). Therefore, the resulting \( \Gamma_L \) is greater than 0.015 corresponding to an attenuation of 18 dB or less. Given the calculated value of ~900 dB loss, we are faced with a large discrepancy from which we conclude that the leakage occurs through a different mechanism.

(2) Propagation through the cladding

This mechanism includes coupling into the cladding directly as well as coupling into leaky modes of the core with subsequent leakage of light into the cladding. In this case the cladding behaves as a "light pipe", i.e., it propagates all light input whether it is coupled into its propagating modes directly or from leaky modes. Therefore, to obtain the intensity coupled into the cladding \( P_{c\text{CL}} \) at the fiber input we integrate the input field distribution over the area of the cladding \( A_{c\text{CL}} \):

\[ P_{c\text{CL}} = P_0 \int_{A_{c\text{CL}}} |F(x, y)|^2 \, dA \]  

(3)

The field \( F \) was evaluated the same way as in the case of propagation by means of leaky mode; again, since an integral over a broad area is taken, variations in approximating the central part between the peaks made no appreciable difference. At the lowest point between the peaks, the detected power is \( P_{c\text{CL}} \Gamma_{c\text{CL}} \), where \( \Gamma_{c\text{CL}} \) is the power attenuation factor for the cladding.

We obtained values \( \Gamma_{c\text{CL}} \) of ~0.0008\( \Gamma_0 \) for the NRL fiber and ~0.0004\( \Gamma_0 \) for the TAU fiber. These values may be limited by diffraction effects in the measurement setup: currently we utilize the on-axis arrangement depicted in Figure 1 which places the fiber, the fiber connector, and a supporting structure in the incoming beam. An effort is under way to replace the on-axis focusing setup with an off-axis one.
Conclusions

In conclusion, we have demonstrated a technique for characterizing rejection of input fields not coupled into the fundamental mode in single mode fibers. The likely mechanism of the undesirable leakage in fibers reported here is propagation through the cladding. We obtained values of the power attenuation factor in the cladding $\Gamma_{CL}$ of $-0.0008/\delta$ for the NRL fiber and $-0.0004/\delta$ for the TAU fiber. The proposed technique provides directly the ratio $\Gamma_{CL}/\delta$ which is a good measure of the undesirable leakage since the useful signal at the output is attenuated by the factor of $\delta$. We consider the measured values of $\Gamma_{CL}$ to be upper bounds for the actual attenuation, since errors are introduced into the measurement by the diffraction off the fiber connector and the supporting structure.

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References


