Design and Investigation of Modal Excitation in Tapered Optical Fiber for a Mode Division Multiplexed Transmission System

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Abstract

One of the main advantages of optical communication is its potential to transmit messages through the same channel via multiplexing. The concept of Mode Division Multiplexing (MDM) technology was first suggested to the telecommunication industries as a substantial solution to decrease the cost per bit of optical fiber transmission. This article aims to transmit information with less possible noise. To achieve this, multiple transverse modes are used to deliver information from the transmitter to the receiver. Our design evaluated a tapered nature that excites a total of 20 modes. In the evaluation, we applied Fourier transformation to the modes. We combined two, three and four modes to test the different complex mode mechanisms they produce in amplitude and phase.

Keywords: Optical Communication, Mode Division Multiplexing, Tapered Fiber, Few-mode Fiber.

1 Introduction

Optical communication provides high-speed, secure, and reliable data transmission over long distances, making it an ideal choice for many applications, including telecommunications, internet services, and data centers (see Figure 1). However, optical fiber has several weaknesses, such as diameter fluctuations (Macedo, L., 2022). As a result, the power carried by a single mode launched at the input end of the fiber is gradually transferred to other modes and then spreads to virtually all propagating modes (Banawan, M., 2022) (Ghazi, S.A.A., 2021) (Ghazi, A., 2021). However, this effect seems to have been overestimated since mode coupling in today's multimode fiber appears quite small.

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Figure 1: Optical Fiber Applications (Dadras et al., 2022)

The distribution of the modes in a steady state among the modes may exceed several kilometers. Therefore, mode coupling (Dadras, M., 2022) (Ghazi, A., 2021) (Ghazi, A., 2021) increases the modulation bandwidth whenever optical power modes carry the information. This leads to a reduced rate of pulse spreading. Unfortunately, modal loss occurs because some power is transferred to radiating modes (Hayashi, T., 2022) (Ghazi, A., 2021). The principle of the tapered waveguide has been implemented in integrated optics. It consists of a thin refractive index film (Butt, M.A., 2023) (Ghazi, A., 2021) that tapers down onto a refractive index medium. It could be either infinitely open or confined within a uniform thickness.

The Gaussian beam (Gambino, F., 2022) was launched into the tapered fiber to excite a plurality of modes created in the tapered waveguide. The phase patterns (Zhong, T., 2022) of the beam were studied and compared to the corresponding amplitude profiles of the modes that were excited. The main beam is strong in the center and gradually loses power as it moves away from its center.

2 Research Background

According to (Butt, M.A., 2023), tapered waveguides have mode conversion capabilities. They efficiently couple light into the sub-nano scale waveguides from an external source. There has been an increased demand for downsized and integrated optics into modern devices. Some of these devices, such as sensors (Wolf, A., 2023), couplers (Lin, T., 2023), filters (Zhang, Y., 2023), modulators (Wang, L., 2023) and splitters (Xu, Q., 2023) to mention just a few.

Tapered waveguides enhance the coupling capabilities through the tapered nature and reduction of the fiber characterized. It can be performed by narrowing the gap to a few hundred nanometers to achieve strong modal overlap (Wang, L., 2023) (Wang, P.H., 2023). Researchers are continuously looking for new ways to excite good quality modes that can be used in sensors, data transmission (Lee, H.C., 2023), and multiplexing (Mo, S., 2023). Tapered fibers are characterized by low-loss coupling because of the optimized design of the guiding core.

Researchers developed tapered waveguides to output a Gaussian mode profile using a single mode. Additionally, they used the fundamental Gaussian beam as the input, which outputs a plurality of higher-order modes that can be used for sensing and data transmission. It is important to mention that the incidence of dispersion occurs because higher-order modes are excited. It can be mitigated by choosing a few modes among the excited modes for data propagation. Accordingly, a few parameters are important to consider when referring to a tapered waveguide. The parameters include the following:

- The length of the waveguide.
- The width and thickness of the thin end.
- The thick end, which effectively affects the dispersion of the waves.

These optical structures make it suitable to adjust them or control them by changing the refractive index of the waveguide so that it can excite a different set of modes. It is worth noting that research on tapered waveguides has mostly been focused on optical waveguides propagating in the single-mode optical fiber domain (Zahra, M.M.A., 2022). A taper can be referred to as a building block for a photonic integrated circuit. It is usually applied when connecting waveguides consisting of different widths. Often, tapers are used in applications like mode converters, multimode couplers, waveguide crossings, waveguide transitions and waveguide gratings.

3 Research Contribution and Organization

Mode conversion occurs between the Transverse Magnetic (TM) mode or the fundamental mode and higher order transverse electric (TE) modes when light is beamed in a waveguide taper. This mode conversion occurs because mode hybridization comes through the waveguide's vertical asymmetry. Therefore, by simulating and designing the tapered waveguide, we seek to determine how higher-order modes are excited to be used for sensing or data transmission.

The rest of the article is structured as follows. Section 2 provides a critical analysis of the related works. Section 3 presents the modeling of our system. The results of simulation experiments and analyzed and discussed in Section 4. A conclusion and some future directions are drawn in Section 5.

4 List of Acronyms

Table 1 presents the used list of acronyms in this paper.

Table 1: Nomenclature

Acrynom	Meaning
FD-BPM	Finite Difference Beam Propagation Method
MDM	Mode Division Multiplexing
TM	Transverse Magnetic
TMI	transverse mode instability
YDF	ytterbium-doped fiber

5 Related Work

In the literature, many researchers and scholars have tested and experimented on modes generated using tapered fiber. For instance, (Ye, Y., 2019) experimentally investigated the transverse mode instability (TMI) of two amplifiers based on ytterbium-doped fiber (YDF) with a uniform core diameter and tapered core diameter. The comparison between conventional uniform fibers and long tapered fibers provided an effective way to maintain beam quality and suppress the generation of nonlinear effects in fiber lasers. Similarly, (Ahmad, H., 2021) achieved high beam quality by incorporating tapered fiber in their fiber laser. Even though this fiber was fabricated using the flame brushing technique, the authors simulated the fiber design using the OptiBPM Design software.

Other applications of tapered fiber were in creating an interferometer for sensing purposes (Zhao, W.M., 2019). The structure was made to reach optimal sensitivity by altering the parameters, including the core lateral displacement, taper waist diameter and cone length. Optimizing these parameters improved sensitivity in the surrounding refractive index achieved through the Finite Difference Beam Propagation Method (FD-BPM). Furthermore, the refractive index was also fundamental when the modes were divided into amplitude and phase profiles. The Fourier Transform calculations conducted in Matlab use the refractive index equivalent of the modes. The authors (Ahsani, V., 2019) (Mahmood, O.A., 2020) conducted experiments on tapered fiber to achieve an ultra-high sensitivity measurement of the refractive index. Conclusively, tapered fiber optimizes the mode quality to achieve higher beam quality. This would produce good modes for data transmission (Ghazi, A., 2019). Similar experiments by researchers involving tapered fiber were conducted by (Mahadzir, N.A., 2021). Using tapered fiber, the refractive index was used by (Ghazi, A., 2020) (Ghazi, A., 2020) to convert to different transverse modes from the fundamental mode for data transmission purposes.

The waveguide designed using tapered fiber was used for the MDM. In the tapered waveguide design, different combinations of multiplexed modes aim to enable the processing of large amounts of data using optical switching apparatus by creating additional data channels. According to (Khan, S., 2020) (Maraha, H., 2020) (Masunda, T., 2018), tapered waveguides reduce coupling loss and help to preserve the beam strength as the waveguide is slowly tapered along the propagation direction.

6 Methods and Materials

We used OptiBPM Design software to structure the tapered waveguide (see Figure 1). It is structured based on the typical tapered waveguide comprising different geometric cross-sections across the waveguide.

The design was made up of a long hose that gradually curls in the middle (with some bends) and ends similar to the beginning. The design was based on few-mode fiber rather than single-mode fiber. The reason is to excite fewer modes that would be excited in multimode fiber but at the same time more than the modes that would be excited in single-mode fiber. The starting point of the waveguide has a width of 20μm, and the ending has a width of 14μm. The waveguide was structured with a length of 800μm, the widest width of 20μm, and the narrowest of 14μm. The difference can be seen along the narrowing pathway, as the waveguide was alternately bent -2 degrees and 2 degrees.

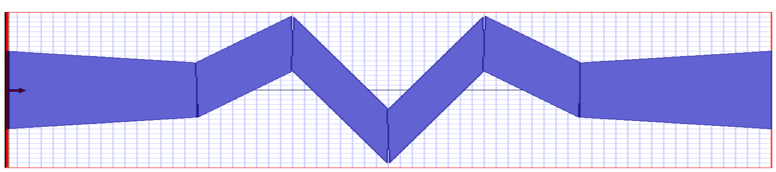

Figure 2: The Layout of the Tapered Waveguide Design

Silica was used as a material in the core and the cladding. It comprises a refractive index of 1.50 and 1.48, respectively. The channel profile and the fiber profile were each set in the following way. For the channel profile, a silica core layer was used with a width of 4μm and a thickness of 2μm. Silica core was used in the Rx and Ry for the fiber profile at 2μm each. The wafer properties were then set by using silica cladding. The simulation involved launching the beam on different subsequent lengths of the waveguide and different widths to establish an optimal design to propagate the strongest beam through the waveguide. Testing different designs and checking the type and number of the excited modes was part of the simulation procedure. Each design that did not meet the criteria of the number of modes and transverse mode profiles would be set aside or amended until the waveguide design in Figure 1 is achieved.

7 Results of the Study

After a Gaussian beam was launched into the waveguide, it excited transverse modes with two profiles for each mode. The first was the amplitude profile, and the second was the phase profile generated by the optical field solver (see Figure 3).

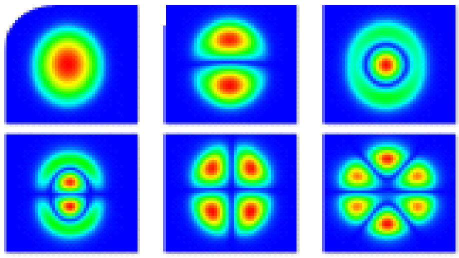

Figure 3: Amplitude Profiles of 6 Excited Modes

Figure 4 illustrates the corresponding phase profiles of the excited modes after the Gaussian beam was launched. To create new combinations of these modes for testing mode strength, the phase and amplitude profiles were inserted into MATLAB and converted from an 8-unit numerical representation to double. We tested mode strength that could be used for sensing or data transmission purposes. Lastly, Figures 5 and 6 show the transformed representation of the modes.

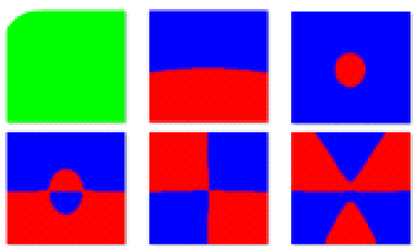

Figure 4: Phase Profiles of 6 Excited Modes

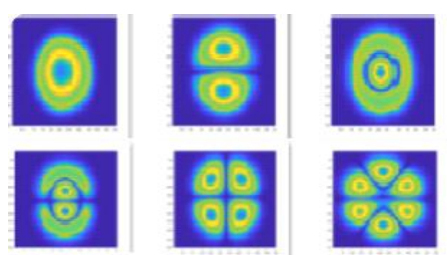

Figure 5: Transformed Amplitude Profiles of the Excited Modes (Numerically)

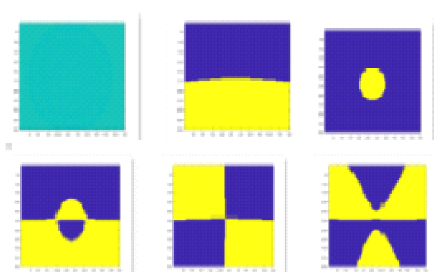

Figure 6: Transformed Phase Profiles of the Excited Modes (Numerically)

Next, we implemented Fourier transformation on the modes by combining the amplitudes and phases of each respective mode. The reason was to be able to create combinations of the single modes. So by forming a complex form of the six modes, each amplitude and phase were multiplied together in the frequency domain (see Figure 7).

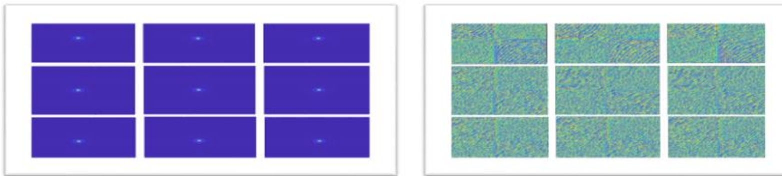

Figure 7: The Fourier Transform of the Combined Single Modes

Further investigations and simulations led to determine different combinations of the modes (being Fourier transformed) to see the amplitude and phase profiles that would materialize from the tapered waveguide. Figure 8 shows the combination of two modes and the resultant profiles.

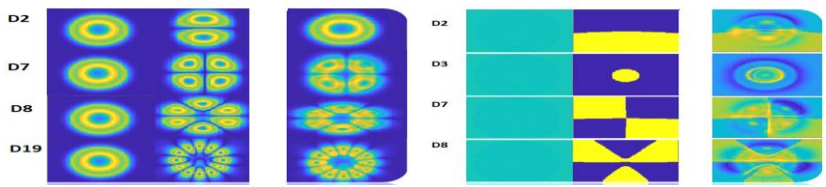

Figure 8: Two Modes Combined Together

In Figure 8, the columns indicate the following:

- Column 1 shows the first mode to be combined.
- Column 2 is the second mode combined during the Fourier transform process.
- Column 3 and the last columns show the new mode profile created when the two Fourier transformed modes are combined together.

The phase profiles are also shown beside the amplitude profiles. The new phase of the combined modes is shown respectively in the last column. Figure 9 illustrates the combination of three modes in both the amplitude and phase domains. The last column shows the new mode created after the Fourier transform. Finally, Figure 10 shows the combination of four modes and their resulting amplitude and phase profiles.

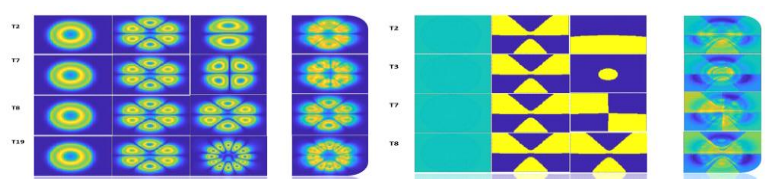

Figure 9: The Fourier Transform of Three Modes Combined Together

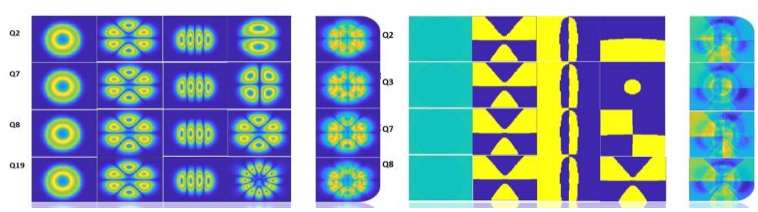

Figure 10: Combination of 4 Modes

8 Conclusion

In this article, we designed a tapered waveguide structure using OptiBPM. To excite a suitable number of modes, the structure was finally reached after several iterations of the design. A total of 20 modes were initially excited from the waveguide, then converted into a numerical form for processing in MATLAB. The combination process of the modes was successfully performed for the two-mode, three-mode, and four-mode combinations by using the Fourier transform. The resulting modes can be used for sensing, MDM in data transmission, and applied using a tapered waveguide.

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