Fiber Eavesdropping Using Tapers in Standard and Trench-Assisted Single-Mode Fibers

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***Abstract*— We investigate taper tapping in three types of single-mode fibers using simulations and experiments: Standard single-mode fiber (SMF), bend-resistant single-mode fiber (BR-SMF) with a shallow index trench, and bend-insensitive single-mode fiber (BI-SMF) with a deep index trench. Both trench-assisted fibers demonstrate a larger mode field expansion than the standard single-mode fiber, making them more susceptible to taper-tapping than standard single-mode fibers. Tapering both SSMF and BR-SMF fibers to as little as 25 µm diameter results in a high information extraction efficiency for an eavesdropper (≥−20 dB) while maintaining low loss for the legitimate channel (≤1 dB), underlining the vulnerability of all fiber types to taper tapping. We also use optical time-domain reflectometry (OTDR) to identify changes in the fiber before and after tapering. Changes in the back reflected power of ≤0.5 dB and ≤0.25 dB are observed in 25 µm tapers in SMF and BR-SMF respectively.**

***Index Terms*— Optical fiber tapering, fiber tapping, physical layer security.**

I. Introduction

DATA transmission through single-mode fiber (SMF) underpins our global communications society [1]. Over the past few decades, there has been an exponential increase in data traffic driven by increasing global connectivity. New technology has been developed and deployed in optical networks to keep up with this demand, and current research trends in ultra-wideband and space division multiplexing [2] seek to address future capacity challenges. At the same time, little attention has been paid to physical layer security. With this in mind, the potential to tap optical fibers directly poses a real threat to secure communications. Optical fiber is easily tapped by inducing a fiber bend that evanescently couples out a small fraction of the signal [3]. As an alternative to bend-tapping, one may also side-polish [3], [4], [5] or taper the fiber to generate an evanescent coupling region. Current methods to protect data utilize encryption methods such as Advanced Encryption Standard (AES) which are expected to become vulnerable to developing quantum computers and harvest now, decrypt later attacks are already anticipated. A complimentary approach which brings additional security is to consider physical layer security. Here, we refer to the use of physical devices such as optical fibers and physical unclonable functions (PUFs) to provide security and optical sensing techniques to detect the presence of an Eavesdropper. Here, we report a theoretical and experimental study of tapering in standard single-mode fiber (SSMF), bend-resistant single-mode fiber (BR-SMF) and bend-insensitive single-mode fiber (BI-SMF). We investigate the impact of taper tapping on the legitimate channel loss, the tapping extraction efficiency attainable by an eavesdropper, and use optical time domain reflectometry (OTDR) to assess the ability to detect the presence of taper tapping.

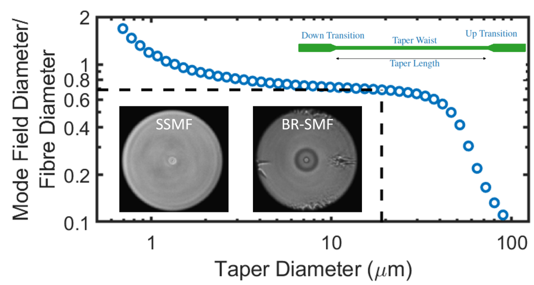

Fig. 1. Simulated normalized mode field diameter and inset bottom fiber optical micrographs. Inset top: Schematic of a double-ended taper structure.

II. Tapping Approaches and Taper Theory

Several approaches to tapping power from optical fibers exist, including macro-bend, micro-bend, etching, splicing in a physical coupler and tapering [3]. The challenge from the perspective of the attacker is how to extract the maximum

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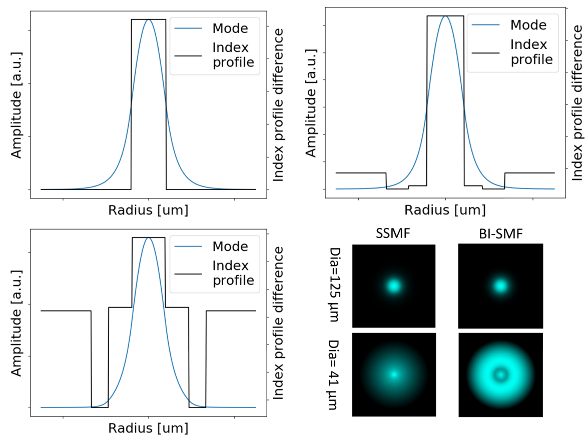

Fig. 2. Normalized LP_{01} mode (left-hand axes) and refractive index profile (right-hand axes) for (Upper left) SSMF, (Upper Right) Prysmian Group BR-SMF & (Lower Left) Prysmian Group BI-SMF (Lower Right) Mode field Distributions for SSMF and BI-SMF at 125 µm & 41 µm taper diameter.

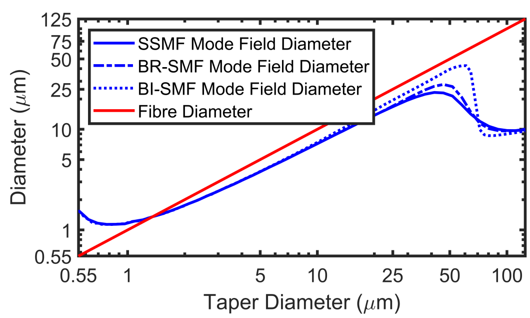

Fig. 3. Simulated mode field diameter at 1.55 µm for SSMF (solid blue) BR-SMF (dashed blue) and BI-SMF (dotted blue) with the taper profile (solid red).

amount of power while inducing the lowest attenuation to the channel (such that the legitimate transmitter/receiver pair does not detect the eavesdropper). The advantage of directly splicing in a permanent coupler is that once in place, this solution is extremely rugged, but due to the high loss observed by the legitimate user, this approach is easily detectable due to the channel disruption during splicing. In this work, we build on our previous experience using clip-on couplers [6] and analyzing fiber tapering, to apply optical fiber tapering [7] to fiber tapping. A schematic representation of a double-ended optical fiber taper is shown in Fig. 1. Optical fiber tapering can in principle allow for adiabatic transitions where the mode field is still guided but where a substantial percentage of the optical field is available to the attacker for tapping purposes. As seen in Fig. 1, as the fiber taper diameter is reduced, the mode field diameter normalized to the cladding diameter starts to approach 1, showing that the optical field is no longer confined only in the cladding diameter glass but can at extremely small diameters (≤1 µm) even extend beyond the fiber boundaries. The gradient change in Fig. 1 at ≈50 µm is the point at which the optical mode transitions from core to cladding guiding. This allows a potential attacker a discrete and tunable method to extract the maximum amount of power for tapping the signal while minimizing the receiver loss.

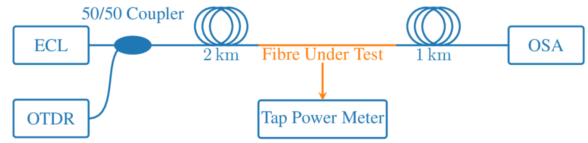

Fig. 4. Experimental setup.

III. Simulations

Before conducting the experimental investigation of tapering to extract power from SSMF and BR-SMF, we carried out simulations of the mode field evolution with the taper diameter for SSMF, BR-SMF and BI-SMF. For this, we use an in-house mode solver to solve the linearly polarized (LP) modes of the fiber geometry [9]. We define the refractive index profile for each fiber type based on the manufacturers' specifications. The refractive index profiles and the LP_{01} mode profile for the untapered fiber geometries are shown in Fig. 2. From Fig. 2, it can be seen that the refractive index profiles of the BR-SMF and BI-SMF have a trench which provides additional confinement and reduces the evanescent field strength in the cladding as compared to the SSMF seen in panel Fig. 2. The confinement provided by the trench reduces the bend-induced losses in bend-resistant and bend-insensitive fibers which then makes these fibers harder to tap power out through bend coupling techniques [10], [11]. Starting from an untapered fiber geometry we solve the LP modes for the SSMF and measure the mode field diameter (MFD), we then reduce the fiber diameter and recalculate the LP_{01} modes in 51 steps to the final fiber diameter of $0.5\mu m$ for SSMF, BR-SMF and BI-SMF. The MFD results are plotted in Fig. 3 for SSMF (solid blue), BR-SMF (dashed blue) and BI-SMF (dotted blue). For comparison, the red solid line shows the relative fiber diameter at each taper diameter. We can observe that for diameters $\geq 1\mu m$ the mode field is completely confined within the physical fiber dimensions. As the taper diameter is reduced, the mode initially expands for all fiber types. Additionally, it can be seen that for the BR-SMF ($28\mu m$) and BI-SMF ($43\mu m$), the mode field diameter (MFD) expands more than in an SSMF ($23\mu m$), which suggests that BR-SMF and BI-SMF are potentially more sensitive to fiber taper tapping than SSMF. The data presented in Fig. 3 is for 1.55 µm, a similar trend with a slightly different magnitude is observed across the c-band (1530-1565 nm). This counter intuitive behavior suggests that BI-SMF and BR-SMF are more susceptible to taper tapping than SSMF. As discussed above, for BR-SMF and BI-SMF which have refractive index trenches of differing depths, as the fiber tapers and the mode field expands the average refractive index difference to the air is reduced due to the presence of the low index trench and as such the mode expands more than SSMF. In the lower left panel of Fig. 2, the mode field profile for BI-SMF and SSMF are shown at different taper diameters, demonstrating the clear change in confinement for the two fiber types as the fiber is tapered. The striking differences occur at a taper diameter $\approx 41.4\mu m$ where for the BI-SMF the mode starts to resemble the two lobe structure of an LP_{02} mode (without the associated phase difference of LP_{02}) due to the strong confinement between the low index trench and the air cladding. Furthermore, in practice, due to the high mobility of fluorine [12] within the amorphous silica matrix at elevated temperatures, the refractive index profile of BR-SMF and BI-SMF could be further modified beyond that caused by the mechanical tapering of the fiber geometry. These results further motivate the need for experimental investigation of power extraction from SSMF and BR-SMF.

IV. Experimental Setup

In this section, we experimentally investigate the tapering of different types of SMF to tap power from the fiber and whether this is detectable to the legitimate user. We investigate two types of SMF: Corning single-mode fiber (SMF-28) and a BR-SMF from Prysmian Group. Optical micrographs of both fiber types are shown in Fig. 1.BR-SMF presents a challenge to the tapping based on macro and micro-bending losses using clip-on couplers [3], [13]. The experimental setup is shown in Fig 4. The ≈4 m fiber under test is placed between a 2 km spool and 1 km spool of Corning SMF-28, which is used to provide a stable propagation length for OTDR measurements and to simulate tapping an SMF mid-span. In practice, mid-span tapping is not an ideal approach because of signal loss during propagation. In practice, one would endeavor to tap as close as possible to the transmitter to extract the maximum possible signal power at the minimum possible tapping ratio. Before the first 2 km spool of SMF a 50/50 coupler is used to combine the test signal (1549.3 nm) with the OTDR (model: Ando AQ-7130) pulses (3 ns at 1550 nm). An optical spectrum analyzer with 0.05 nm resolution records the transmitted spectrum at the output. Tap power is simply measured (only a fraction of the evanescent field is captured by the power meter) with an inline power meter (Thorlabs model S132C) positioned parallel to the tapered fiber section. The legitimate receiver loss and tap extraction efficiency are calculated from the measured spectra and power meter values. Receiver loss is defined as:

$$L_R = -10\log_{10}\left(\frac{P_{withtaper}}{P_{withouttaper}}\right), \quad (1)$$

where $P_{withouttaper}$ is the measured receiver power before tapering and $P_{withtaper}$ is the measured received power after tapering. The extraction efficiency is defined as:

$$\eta = 10\log_{10}\left(\frac{P_{tap}}{P_{in}}\right), \quad (2)$$

where P_{in} is the transmitted power and P_{tap} is the measured power from the inline power meter placed along the length of the taper after the tapering process has been completed. The fibers were tapered to outer diameters in the range 125 µm to 25 µm with a Fujikura FSM-100P+. The tapers produced in this work have a complete up-and-down transition with a length of 12 mm and a waist length of 2 mm, resulting in a total taper length of 26 mm.

V. Results

In Fig. 5a and 5b, the receiver loss and extraction efficiency results are presented for different taper diameters for both SSMF and BR-SMF. In Fig. 5a, the additional loss measured by the receiver increases as the taper diameter is reduced, reaching a maximum loss of ≈0.9 dB for a 25 µm diameter taper. The corresponding extraction efficiency steadily increases from ≈ −60 dB at 125 µm diameter to ≈−12 dB at diameter of 25 µm. These metrics are potentially extremely concerning for network operators as the legitimate receiver loss and extraction efficiency fall within the limits identified in [8] of receiver loss ≤2 dB and $\eta \geq -18.5$ dB necessary for a successful optical coupler. In Fig. 5a the change in gradient at 50 µm is likely due to the transition from core to cladding guiding seen in Fig. 1 combined with imperfections in the tapering which results in a non-adiabatic transition. Such a gradient change is not seen in Fig. 5b, likely due to the extra confinement provided by the low-index trench in the bend-resistant fiber. In Fig. 5b, the receiver loss and extraction efficiency are plotted for BR-SMF. The measured receiver loss of 0.45 dB and maximum extraction efficiency ≈−20 dB are both lower than for SSMF. At 0.5 dB tapping loss for the legitimate channel, the SSMF exhibits −35 dB of extraction efficiency, while the BR-SMF exhibits -20 dB of extraction efficiency. This shows that the BR-SMF is easier to tap than the SMF and allows for an eavesdropper to go unnoticed. For BR-SMF the tapering process combined with the simple approach to measuring the out-coupled power is not as refined as for SSMF. Furthermore, the high mobility of fluorine [12] means it is possible that the unoptimized taper process causes diffusion of the fluorine changing the index profile and which limits the mode field expansion as compared to theory. However, an extraction efficiency of ≈−20 dB implies that the eavesdropper would see the same signal power as a legitimate receiver ∼100 km downstream from the tap location, which represents a significant and hard to detect threat at 0.5 dB of added insertion loss to the legitimate channel. Furthermore, the approach utilized here of measuring only side-scattered power is extremely crude and a more refined approach could certainly improve the extraction efficiency. In Fig. 6, OTDR traces for SSMF and BR-SMF for unstripped (meaning the polymer coating still mechanically protects the fiber), stripped without taper and stripped with taper fiber configurations are shown. The OTDR traces show a peak with width ≈ 4 *m* centered around 2006 m and 2008 m for SSMF and BR-SMF respectively, which indicates reflections from multiple fiber connectors and splice points which cannot be individually resolved due to limited OTDR spatial resolution and dynamic range. This section of fiber is used for the repeat taper manufacturing and power measurements taken in this investigation. The lack of power drop after the reflection point is due to the limited dynamic range of the OTDR and that the back scattered power is already below the noise floor before and after the reflection point. Finally, the increase in backscattered power for the fiber configurations stripped without taper and stripped with taper and likely due to a combination of mechanical perturbation of the fiber by the fiber holding blocks and due to the imperfect tapering process causing additional reflected power. For a SSMF (Fig. 6a) it can be seen that after the tapering, a small difference of ≤0.5 dB in backscattering levels at the taper can be observed. However, no change in power level before and

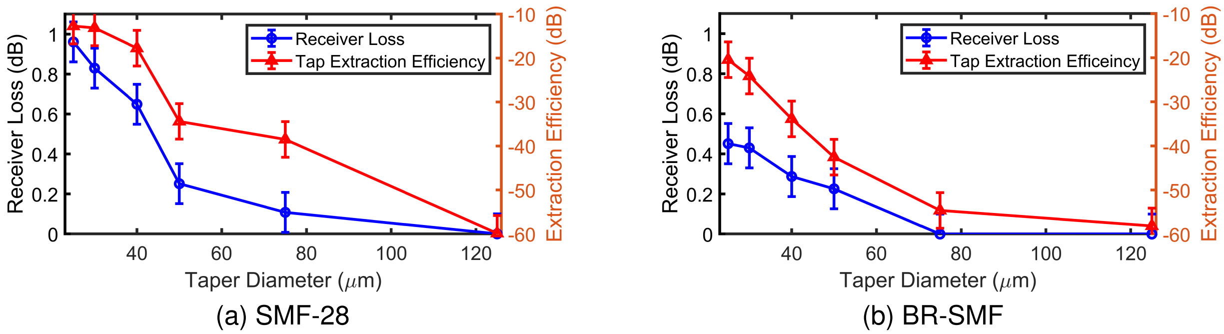

Fig. 5. Receiver Loss (blue and left-hand axes) and extraction efficiency (red and right-hand axes) with error bars for different SMFs. (a) Corning SMF-28 (b) Prysmian Group BR-SMF.

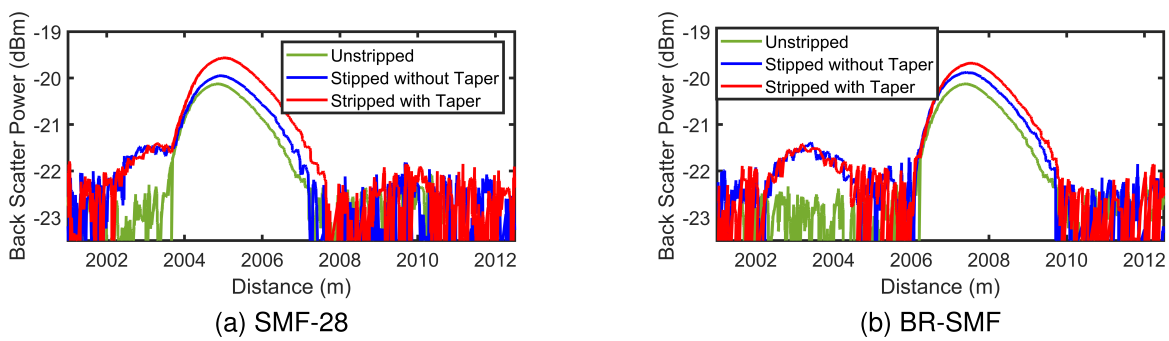

Fig. 6. OTDR of different SMF unstripped (green) stripped without taper (blue) and stripped with taper(red) 25 μm diameter taper between OTDR traces for untapered and tapered fiber. (a) Corning SMF-28 (b) Prysmian Group Bend Resistant SMF.

after the taper can be observed, most likely due to the limited dynamic range of the OTDR. The limited spatial resolution of the OTDR of ≈5 cm, which is ≈ 2× longer than the total taper length, makes detecting the taper directly impossible. Furthermore, for the BR-SMF (Fig. 6b), there is a small (≤0.25 dB) difference in the observed backscatter level at the taper position.

VI. Conclusion

While trench-assisted single-mode fibers are known to be more resilient to bend-tapping, we showed that tapering the fiber expands the mode field more strongly for trench-assisted fibers compared to standard single-mode fibers. This makes those bend-insensitive fibers more vulnerable to eavesdropping. We experimentally confirmed our theoretical predictions and showed that for an identical 0.5 dB of taper-induced loss on the legitimate channel, a bend-resistant fiber leaks 15 dB more power to an eavesdropper than a standard single-mode fiber. We also investigated the OTDR signatures of taper-tapping, which point to the difficulties in identifying a taper-tapping eavesdropper. These results suggest that taper tapping in SMF presents a legitimate challenge to the security of optical fiber networks and that using bend-resistant and/or bend-insensitive SMF does not provide enhanced physical layer security against taper tapping.

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