Endlessly adiabatic fibre

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Abstract: An optical fibre with a logarithmic index profile can be adiabatically tapered over any length, no matter how short. We report an experimental approximation to such a fibre.
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1. Introduction

When an optical fibre is tapered, it is well-known that the transition must exceed a certain minimum length for the taper to be adiabatic [1,2]. If it is shorter, light couples from the fundamental mode to other modes, which in single-mode fibre leads to loss. This limitation on the shortness of tapers constrains the size of components such as fused couplers, and limits the scalability of spatial multiplexers such as mode-selective photonic lanterns [3,4].

We describe here an idealised fibre where the minimum taper length is zero. That is, *any axi-symmetric taper in the fibre is adiabatic*. We also report an experimental version of the fibre which, despite practical compromises, yields a low-loss taper with a length and profile that cause very high loss in a standard telecoms fibre.

Mathematical criteria exist that delimit the local taper angle in adiabatic tapers. The most useful for us is derived from the "weak power transfer" criterion of Love et al [1] with our own modifications [3]:

$$\left| \frac{2\pi}{(\beta_1 - \beta_2)} \frac{d\rho}{dz} \int \Psi_2 \frac{\partial \Psi_1}{\partial \rho} dA \right| << 1 \tag{1}$$

where $\Psi_1(r)$ and $\Psi_2(r)$ are the field distributions of modes (with propagation constants β_1 and β_2) that may couple, ρ is the fibre's size (eg its outer diameter) and z is the coordinate along the fibre. We see that the taper gradient $d\rho/dz$ is restricted by $\partial\Psi_1/\partial\rho$, representing how the mode field varies with the fibre's scale [3,4]. For example, Fig. 1(a) shows the calculated Petermann-II mode field diameter [5] (MFD) at $\lambda = 1550$ nm of a step-index telecoms fibre (Corning SMF-28) versus outer diameter. The MFD varies substantially with fibre diameter, restricting the maximum taper gradient. Shrinking the cladding [3], grading the index profile in the core (while retaining a uniform outer cladding) [4] or microstructuring [6] can reduce the MFD variation somewhat, but do not eliminate it.

Now imagine a fibre where the mode does not change at all with fibre size, so $\partial\Psi_1/\partial\rho = 0$. The taper gradient $d\rho/dz$ can then take any value and an axi-symmetric taper can have any length, even zero, and still be adiabatic.

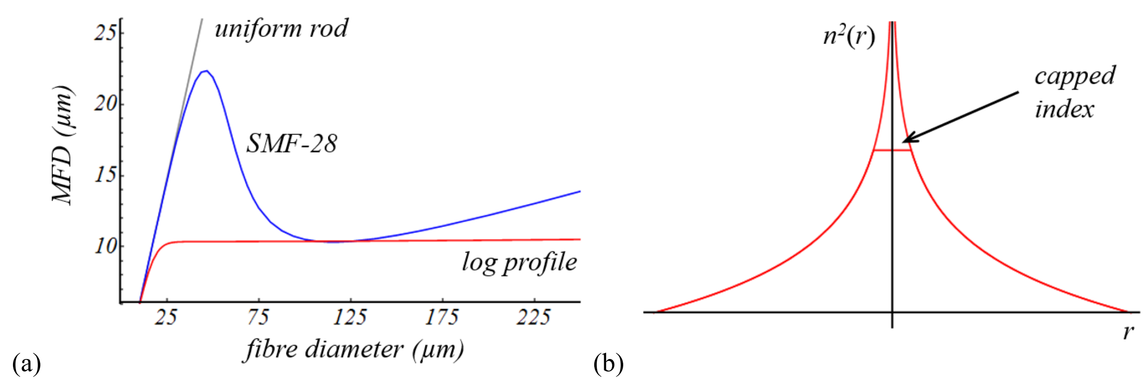

Fig. 1. (a) The calculated MFD of (blue) SMF-28, (red) a realistic log-profile fibre with $NA = 0.095$ and (grey) a uniform silica rod, as functions of outer diameter. (b) A logarithmic index profile, showing how it can be capped near the axis.

2. Logarithmic index profiles: ideal and practical

An idealised fibre with a logarithmic refractive-index profile $n(r)$ is an example of such a fibre:

$$\begin{aligned} n^2(r) &= n_0^2 - NA^2 \ln(r/\rho) \\ &= n_0^2 + NA^2 \ln(\rho) - NA^2 \ln(r) \end{aligned} \tag{2}$$

where r is the radial coordinate, n_0 and NA are constants, ρ is the fibre size and ln is the natural logarithm, Fig. 1(b). The profile is un-clad, continuing all the way to infinity. We see from Eq. (2) that a change in fibre size ρ along a taper only changes the additive constant $n_0^2 + NA^2 \ln(\rho)$. Thus tapering affects the "background" index but has *no effect on the variable part of the profile*, $-NA^2 \ln(r)$. Since it is the variation of an index profile that determines the mode field distribution, the mode will be independent of the fibre's scale: $\partial\Psi_1/\partial\rho = 0$. Thus the fibre can form adiabatic tapers of any length. (Fresnel reflections due to the varying background index will be very small.)

The scalar wave equation was solved numerically to find the (invariant) fundamental mode of the fibre, shown in Fig. 2(a) with that of SMF-28 at $\lambda = 1550$ nm. When the constant $NA = 0.095$ the MFD of 10.4 µm matches that of SMF-28. In this case the overlap between the simulated modes of the fibres corresponds to an idealised splice loss (quantifying how similar the two field distributions are) of 0.015 dB.

(a)

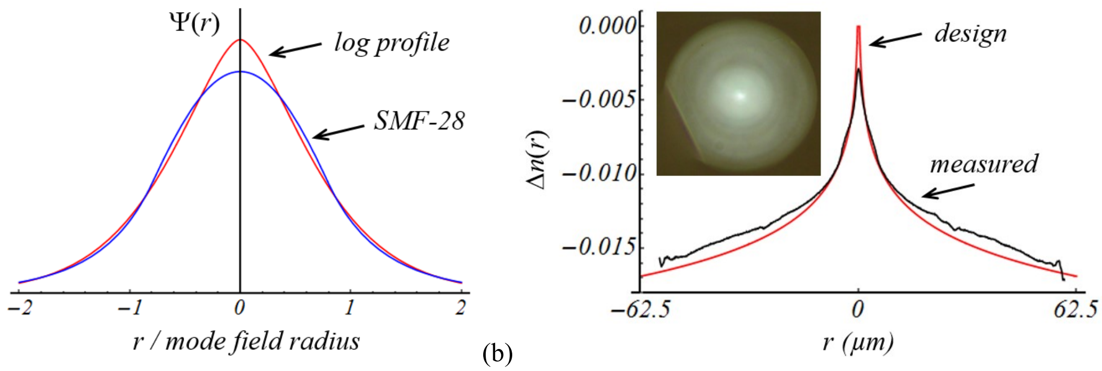

Fig. 2. (a) Calculated fundamental-mode field distributions of (blue) SMF-28 and (red) the log-profile fibre, versus radial coordinate r in units of the mode field radius. (b) Index profiles, relative to undoped silica, of (red) the capped log-profile design and (black) a measured experimental fibre of 116 µm diameter drawn from a PCVD preform. Inset: Micrograph of the 125 µm diameter log-profile fibre.

The ideal fibre is unrealistic in two senses. Firstly, the log function is infinite at $r = 0$, so the index $n(r)$ must be capped to a finite value near the axis, Fig. 1(b). This has little effect if the cap region is small enough. For example, if the cap diameter is 5.6% of the MFD, the effect on the mode is not noticable on the scale of Fig. 2(a): the simulated overlap between modified and unmodified modes corresponds to a splice loss of 0.00004 dB!

Secondly, the fibre must have a finite outer diameter, which we chose to be 125 µm. This has no effect on the mode of the untapered fibre. However, if the fibre is tapered small enough its reduced outer diameter starts to influence, then dominate, the guided mode. The calculated MFD of the fundamental mode of a realistic log-profile fibre with a capped profile and a finite diameter is plotted in Fig. 1(a). Although constant over most of the range, for diameters smaller than 25 µm the MFD curve starts to follow that of SMF28, and indeed of a uniform glass rod, as the light becomes guided by the fibre's outer boundary in all three cases. In this range we therefore expect the criterion for adiabaticity to limit the taper gradient - though tapered fibres are quite resistant to mode-coupling loss once the light fills the cladding anyway [2].

Fig. 2(b) shows the final design of a realistic log-profile fibre designed for splice-compatibility (both optical and mechanical) with SMF-28, with $NA = 0.095$ and an outer diameter of 125 µm. The index is capped to that of undoped silica ($\Delta n = 0.000$) over a central diameter of 0.6 µm (too small to see in the figure). The overall range of refractive indices is 0.017, which is well within the capabilities of vapour-phase preform fabrication techniques.

3. Experiments

We made a preform by doping fused-silica glass with fluorine using PCVD [7], which builds complex profiles from thousands of thin layers with their own compositions and refractive indices. The profile's maximum index matched undoped silica. The layers were deposited inside an undoped substrate tube, which was mechanically removed afterwards. The experimental index profile in Fig. 2(b) was measured by the refracted near-field technique (Exfo NR-9200HR) from a short piece of test fibre drawn from the preform. The match between design and measurement is close, and the simulated splice loss between the modes of the measured and design profiles was <0.02 dB.

A longer length of fibre of 125 µm diameter was drawn from the preform, Fig. 2(b) inset. 1.5 m of it was fusion-spliced between an input length of SMF-28 carrying light from a 1550 nm laser and an output length of SMF-28 connected to a detector, ensuring single-mode output. To explore whether higher-order modes were excited in the log-profile fibre, we gently disturbed it by hand. If higher modes were present, we would see an output variation due to multi-path interference. The observed variation of <±4% indicates that the first splice coupled <2% of the input light to higher modes that reach the second splice. Our later taper-loss experiments were therefore substantially single-mode measurements. We could then also take the 0.4 dB decrease in transmisssion, measured when the second splice was made, to represent a single-mode splice loss between the two fibres.

More-robust bending caused bend loss. Winding three turns of the fibre around a 25 mm diameter mandrel caused 0.6 dB of loss, and a 10 mm turn caused complete loss of light. This bend sensitivity is surprising, since the evanescent field of the simulated mode decays with r roughly as quickly as that of SMF-28. However, it does confirm the minimal transmission of higher modes, since their bend sensitivity will be even greater.

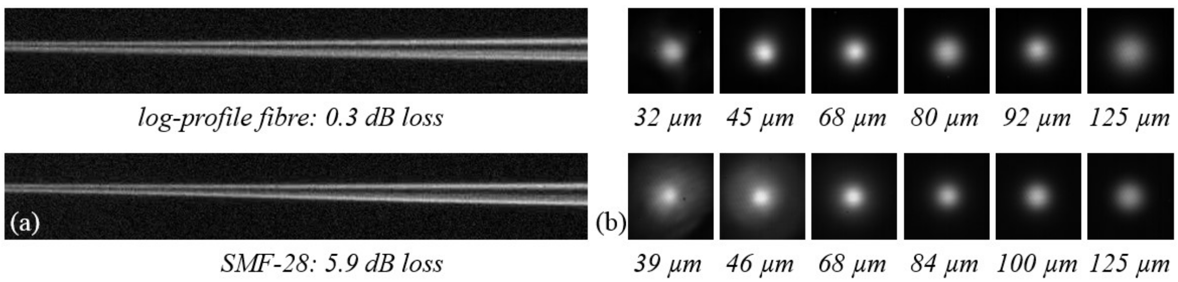

Fig. 3. (a) Micrographs of the short (1.9 mm) transitions of biconical tapers in (top) the log-profile fibre and (bottom) SMF-28. The field of view is about 2.6 mm long. (b) Single-mode near-field images at the output of (top) the log-profile fibre and (bottom) SMF-28 when tapered to the indicated diameters.

The fibre was then tapered to a 10 mm waist of diameter 30 µm while monitoring its transmission. The two transitions in the biconical taper were linear, and 1.9 mm and 21.2 mm long. We wanted to measure the loss of just one short transition; by pairing it with a long transition known to be adiabatic in SMF28 (biconical tapers with two long transitions had losses as low as 0.1 dB), we avoid multi-path interference that would complicate interpretation of our measurements. The loss of the tapered log-profile fibre was 0.3 dB, whereas the loss of a piece of identically-tapered SMF-28 was 5.9 dB, confirming that a taper short enough to cause high loss in SMF-28 was adiabatic in the log-profile fibre. Images of the short tapers in both cases are presented in Fig. 3(a), showing that their lengths and shapes were comparable.

Another piece of the fibre, again spliced at its input to SMF-28, was tapered down to 30 µm diameter over a length of 6 cm. Equally-magnified near-field images of the output were measured using a microscope objective and camera, as the output end of the fibre was cleaved along the taper, Fig. 3(b). The images show how little the mode pattern changes with fibre diameter compared to that of SMF-28, especially for the smaller diameters.

4. Conclusions

We have shown that fibres with an idealised logarithmic index profile can form adiabatic tapers of any length. This remains the case, for local diameters larger than the mode size, in realistic fibres that avoid infinities in index and size. We made a practical approximation to such a fibre, and demonstrated a large reduction in taper loss compared to a similarly-tapered step-index fibre. The fibre can be designed to be splice-compatible with step-index fibre, allowing short lengths of it to be used to make compact low-loss taper components (such as fused couplers and photonic-lantern multiplexers) that are compatible with widely-used fibre types.

5. References

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