Photonic crystal fibre tapers and devices

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Abstract: Tapering (heat treatment after fabrication) can radically change the properties of photonic crystal fibres over centimetre lengths. Such transitions give useful fibre devices, including low-loss interfaces to dissimilar fibres, waveguides and other optical systems.

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1. Tapering of photonic crystal fibres

Tapering is used to make standard single-mode fibres (SMFs) non-uniform over cm lengths. The fibre is stretched while being heated, forming a narrowed waist connected to untapered fibre at both ends by transitions, Fig. 1. "Holey" photonic crystal fibres (PCFs) can also be tapered, to yield a low-loss interface between the fibre and something with a dissimilar mode size, eg another fibre [1-7]. It can also form devices with a short interaction region (of some sort) within the PCF, simultaneously making a modified fibre and interfacing to it [8-20]. However, whereas SMFs are only reduced in scale, in PCFs the holes can also change size (under surface tension) relative to the fibre as a whole. This extra degree of freedom makes the process harder to control, but also greatly enriches the range of possible structures. To characterise tapered PCFs, optical microscopy, SEM and transmission measurements have been supplemented by AFM [21] and transverse scattering [22].

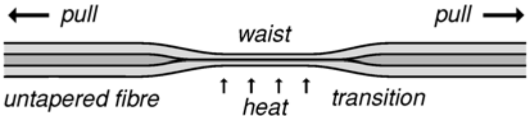

Fig. 1. Schematic of fibre tapering.

2. Fast-and-cold

To avoid hole shrinkage, the PCF is tapered "fast and cold" to reduce the time available and the shrinkage rate. It can be used to interface to other fibres [1,2] and waveguides [3,4]. The OFS grapefruit fibre has been tapered to yield a highly-nonlinear 2.5-µm core interfaced to SMF [8,9], an interface to a rib waveguide [4] and devices with holes filled with various materials [10]. The ability to control dispersion in tapered PCFs gives the fibre unique nonlinear properties, for example in short transitions [11], and in waists where the core diameter is less than 1 µm yet the cladding has a high air-filling fraction [12,13]. It is hard to fabricate such a low-loss submicron-core fibre directly and hard to couple light into it, two problems that tapering of a bigger fibre solves at once [12].

3. Slow-and-hot

To change the relative hole size, the PCF is tapered "slow and hot" to give surface tension time to act. Indeed, the fibre can simply be heated for a time without stretching at all. The mode size changes as the holes shrink, so the transition can be used to match dissimilar fibres [5]. The sizes or positions of the holes can be modulated by periodic heating or twisting of the fibre, yielding long-period gratings and localised directional couplers [14,23] or rocking filters [15] (respectively) that are much less temperature-sensitive than in SMF.

As a PCF is tapered (whether or not the holes shrink relative to the fibre) the light becomes less well-confined to the core and leakage loss can be a problem [24]. Light eventually couples to modes of the fibre's extensive solid outer cladding, preventing adiabatic propagation [25]. So, unlike SMFs, high loss results when a PCF is tapered until light fills the cladding (though it can be exploited for sensors [16]). The exception is the grapefruit fibre, whose outer cladding is thinner than the holes [17]. Hence PCF fused couplers to date have been very lossy [26,27], though tap coupling is possible with low loss in the through arm [28].

Leakage loss can be prevented by pressurising the holes so they expand during tapering [2,18]. This has given low-loss transitions down to very small cores, and new nonlinear devices [29]. Selective pressurisation allows changes in core shape as well as size, for interfacing to non-circular modes [6] and making new types of mode convertor [7]. Lateral access inside a PCF has been achieved by allowing a pressurised hole to explode [19].

Fibre drawing of a core-less PCF preform with an SMF inside forms a transition between the SMF and the drawn PCF, the SMF supplying the core material [30]. This enables a low-loss splice-free interface from the SMF to any type of index-guiding silica PCF, including multi-core fibres. The technique can also yield mode convertors [7], and a method for achieving single-mode performance in multimode fibre devices [31].

4. Photonic bandgap fibres

Unlike index-guiding PCFs, the loss of a bandgap fibre is low only in bands with wavelengths that scale with the structure. If the fibre is tapered more than slightly, no one wavelength is guided in the core along all the transition (Fig. 2) and, because core light is in a very high-order mode (the true fundamental mode being a cladding mode), adiabaticity into a cladding mode is almost impossible. Bandgap fibres tapered by more than a few % in diameter are therefore very lossy [33], though slight tapering can usefully narrow the transmission spectrum [20].

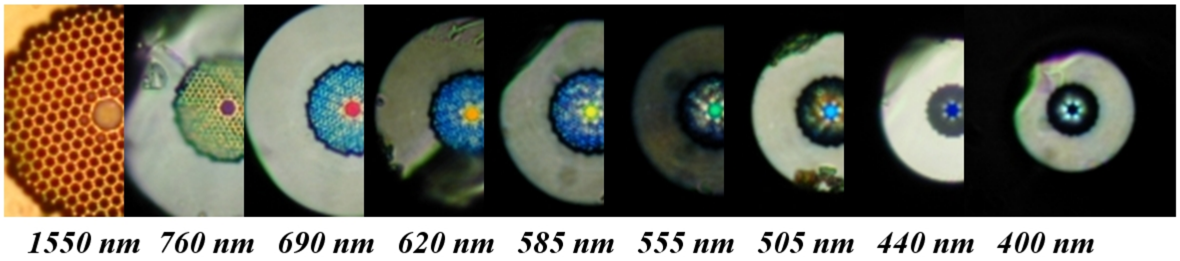

Fig. 2. A montage of micrographs (to the same scale) of a hollow-core PCF tapered fast-and-cold to different diameters [32]. Each sample of taper waist was uniform, ~2 cm long and illuminated from the far end with white light. The untapered fibre guided light with wavelengths around 1550 nm. The number below each image is 1550 nm scaled by the diameter reduction ratio, a wavelength matching the colour of the light in the core. If the images were sections along a taper transition, no single wavelength of light would be guided everywhere along it.

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