Novel Fibers for Ultra-Short and High-Power Pulses

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Abstract: Light propagation in higher-order modes of few-mode fibers leads to unique dispersive properties that are challenging or impossible to achieve in conventional fibers. We will describe their application to devices utilising high-peak-power and ultra-short pulses.

OCIS Codes: (320.7080) Ultrafast devices; (060.5530) Pulse propagation and solitons

1. Introduction

Fiber-coupled and fiber-based laser sources with ultra-short pulses (ps-fs) have recently received a lot of attention because of the high peak powers they can provide for a variety of applications. However, the high peak-powers also make the pulses susceptible to nonlinearities when propagated in a fiber. In addition, due to their large bandwidths, they rapidly disperse (and hence temporally spread and decrease in peak power) within a few meters of propagation in fibers. Hence, fibers used for ultra-short-pulsed devices and applications need to be optimised in terms of both their nonlinear and dispersive properties. The ratio of the dispersion length L_D, to nonlinear length L_{NL}, governs whether pulses propagating in a fiber primarily undergo dispersive or nonlinear changes. For $L_D/L_{NL} << 1$, nonlinear effects are not important, and the pulse operates in the dispersive regime; for $L_D/L_{NL} >> 1$, nonlinear phase changes primarily dominate; and for $L_D/L_{NL} \sim 1$, both effects play a role. This quantity is directly related to fiber properties by $L_D/L_{NL} \propto 1/D \cdot A_{eff}$ where A_{eff} is the effective area of the spatial mode of the fiber in which propagation occurs, and D is its dispersion[1]. In addition, obtaining transform limited outputs from such devices also requires that the pulses be completely dechirped. Hence, fibers also need to be optimised for relative dispersion slope, RDS, given by $RDS = D_{slope}/D$ where D is dispersion and D_{slope} is its slope with respect to wavelength.

Conventional single mode fibers (SMF) offer limited flexibility in obtaining different L_D/L_{NL} or RDS values. In the technologically important wavelengths of 700 – 1060 nm, their dispersion parameter is always negative (normal), and their A_{eff} are typically small (10-30 μm^2). Photonic crystal (PCF) and air-guided photonic bandgap (PBG) fibers have recently generated a lot of interest due to their enhanced dispersion-engineering capabilities.

This talk will review an alternative class of fibers that offer the possibility of obtaining a range of dispersion, RDS and L_D/L_{NL} values. These fibers are realised by conventional fabrication techniques, and hence share the low-cost, repeatable and polarisation-independent attributes of SMFs. Instead of propagating light in the fundamental mode of a fiber, we will show that signal excitation in a single, well-defined higher order spatial mode (HOM) of a specially designed fiber can offer a vastly enhanced design space for tailoring dispersion. A common element to all the devices described here is an in-fiber grating, which excites the desired HOM at the input, and then converts the signal back to the fundamental, Gaussian-shaped mode at the output – this process is highly efficient, and converts > 99% of the energy over bandwidths of 50 to 100 nm into the desired HOM[2], thus maintaining effectively single-moded behaviour even though the fibers are themselves few moded.

2. Highly dispersive fibers

A commonly adopted solution for transmitting or delivering high-power pulses with fibers is to use large-A_{eff} fibers, since this decreases L_D/L_{NL}, thereby mitigating nonlinearities[3]. However, arbitrarily increasing A_{eff} causes two problems: it makes the fiber more bend-sensitive, and it makes them multimoded and hence susceptible to modal noise[4]. Note, however, that L_D/L_{NL}, can be decreased and nonlinearities mitigated also by increasing the dispersion of the fiber. The advantage of this approach would be the ability to use a small-A_{eff}, bend-resistant, robust fiber as, for example, may be needed for two-photon biological imaging studies where the fiber is used as the delivery mechanism in a flexible endoscope[5].

Fig. 1

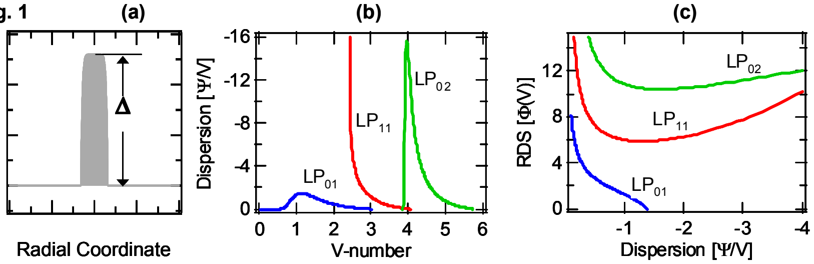


Figure 1 illustrates dispersion-engineering design-space available for different spatial modes in fibers. Assuming a simple step-index fiber-waveguide with a given index contrast Δ, one can analytically obtain dimensionless parameters ψ and ϕ, representing, respectively, dispersion and RDS. As shown in Figs. 1b and 1c, the magnitude of *D* as well as *RDS* increases with mode-order. This implies that for similar waveguide dimensions and Δs, and hence nominally similar A_{eff} values, HOMs will yield significantly lower L_D/L_{NL} values and a larger range of achievable *RDS*.

Fig. 2

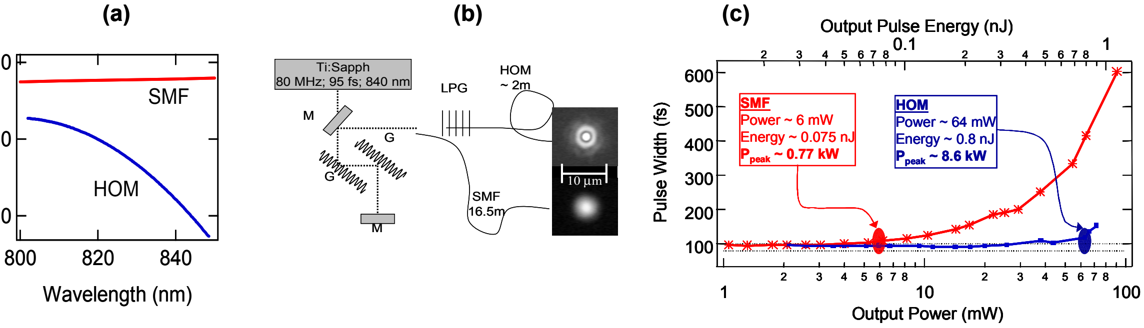


Figure 2a contrasts the dispersion of the LP_{02} mode of an experimentally realised HOM fiber with that of SMF (both fibers are optimised for operation in the 800-nm wavelength range. Both fibers have small A_{eff} (14-18 μm^2), and hence enable robust, bend-resistant light propagation. However, since the magnitude of the dispersion of the LP_{02} mode in the HOM fiber is almost an order of magnitude larger (D_{LP02} ~ -900 ps/nm-km) than SMF at 840 nm (the operation wavelength), the L_D/L_{NL} ratio of the HOM fiber is 10x lower than that of SMF. This enables nonlinear-distortion-free fs-pulse propagation with an order of magnitude larger pulse energies (up to ~ 1 nJ) than that possible with SMF, as shown in Fig. 2c (schematic of experiment, showing dispersion-compensated pulses delivered from a Ti:Sapphire laser using both the fibers is shown in Fig. 2b – also shown here are the mode images for the two fibers). Such HOM fibers would prove very attractive for building flexible 2-photon endoscopes and delivery media, since they offer nonlinearity-free performance without the need for sacrificing bend-resistance and robust propagation (by increasing A_{eff})[6].

3. Anomalous Dispersion

A majority of short-pulse devices operate in the spectral range of 700-1100 nm, where conventional SMF can yield only normal (negative) dispersion. Small-core PCFs have generated much interest due to their ability to achieve positive dispersion in this wavelength range[7]. HOMs can yield large anomalous dispersion in this spectral range, with A_{eff} ~10x larger than PCFs, due to their unique modal evolution properties. Figure 3 shows the dispersive properties of the LP_{02} mode of different HOM fibers – both large positive dispersion as well as multiple zero-dispersion wavelengths can be achieved in the spectral range of 700-1100 nm. In general, it is possible to tailor the (anomalous) dispersion of HOMs with design flexibility akin to SMF at 1550 nm, making this a highly versatile platform for dispersion engineering at these wavelengths.

Figure 4 illustrates an experimental realisation of one such fiber. The module-schematic illustrated in Fig. 4a shows that the device comprises LPGs for mode-conversion at both the input and output – thus, the device is terminated with SMF-like pigtails and can be integrated with other fibers/fiber-devices with a simple splice. The 1-dB operation bandwidth of this device was 51 nm, and insertion loss, including all splice contributions, was only ~ 0.1 dB (Fig. 4b). Figure 4c shows the dispersion of the module (measured by spectral interferometry[8]), and the calculated A_{eff} (44 μm^2 at 1080 nm).

Fig. 3

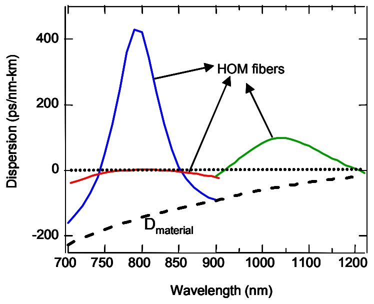
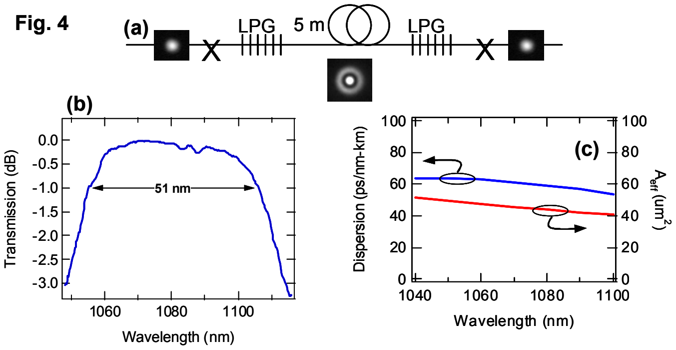
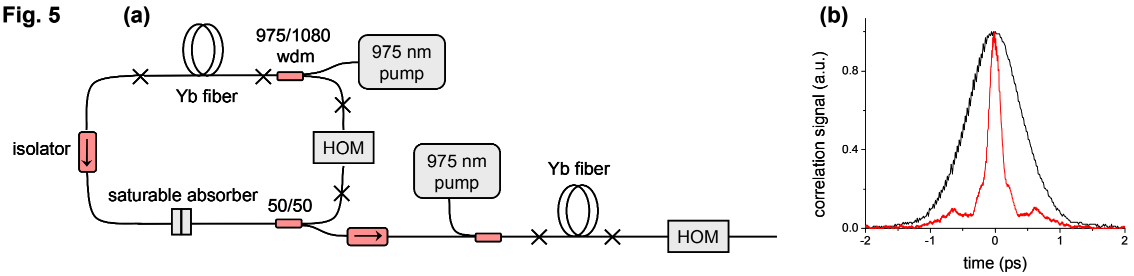


Fig. 4



This fiber was used as the dispersion compensating element inside a Yb ring laser modelocked with a carbon-nanotube based saturable absorber[9], as shown in Fig. 5a. Past demonstrations of Yb ring lasers modelocked with carbon nanotubes required bulk gratings for dispersion compensation. The output of the oscillator was then amplified with a second Yb-doped fiber amplifier, and the resultant chirped pulses were de-chirped with a second HOM fiber module. Thus, a 1-nJ, 137-fs wide pulse train with a time-bandwidth product of 0.43 was obtained (see Fig. 5b – black curve: after Yb amplifier fiber; red curve: after HOM).

Fig. 5



This novel class of HOM fibers will have far reaching implications for the design of fiber-based short-pulse devices in the visible and near-IR wavelength ranges, because this fiber provides the low-loss, bend- and nonlinearity-resistant operation of conventional fibers in a wavelength range where conventional fibers cannot achieve anomalous dispersion[10].

4. Summary

In summary, HOMs in specially designed, few-moded fibers, fabricated by conventional fabrication techniques, offer significantly greater flexibility in tailoring dispersion and A_{eff} compared to SMF. Since these two quantities are critical in determining the behaviour of ultra-short pulses, HOM fibers are attractive for building all-fiber short-pulse delivery media, sources and amplifiers.

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