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High-Energy Four-Wave Mixing, with Large-Mode-Area Higher-Order Modes in Optical Fibres

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Abstract *We demonstrate, for the first time, four-wave mixing, in the 1-μm spectral regime, in an LMA silica fiber. Pumping a 618-μm^2 LP_{07} mode (λ_{ZDW}=1038.4 nm) with a 1064.6-nm Nd:YAG laser results in the generation of modulation instability, and multiple Stokes/anti-Stokes lines, opening up the prospect of high-energy parametric processes with fibers.*

Introduction

While fiber lasers have made tremendous progress in power scaling in the 1 and 2-μm wavelength ranges, power scaling in other technologically attractive spectral ranges, such as the blue-green, eye-safe, or the mid-IR wavelengths, has been limited because suitable dopants are not readily available. Wavelength conversion via four-wave mixing (FWM) in fibers is an attractive means of accessing these spectral ranges[1], and dispersion design with photonic crystal fibers (PCFs) has enabled this[2]. Unfortunately, the requirement that the zero-dispersion-wavelength (ZDW) of the fiber be in the vicinity of the pump laser, combined with the fact that PCF designs fundamentally require reducing mode area (A_{eff}) with pump wavelength, implies that this concept is not power/energy scalable.

Here, we propose a new path for exploiting fiber nonlinearities without being constrained by mode area and thus power-level limitations. This is based on the realization that ZDW in higher order modes (HOM) of fibers scales with mode order in analogy to ZDW scaling with mode area in PCFs[3]. Thus phase matching for the nonlinear process is achieved by choosing the interacting modes accordingly[4,5]. This, combined with the experimentally-proven fact that HOMs are more stable than the fundamental mode of suitably designed large A_{eff} fibers[6], enables the development of fibers that can yield wavelength conversions at dramatically higher power levels.

Fiber Design

The four wave mixing fiber used for the experiments is a double-clad fiber fabricated by Nufern Inc. A microscope image of the end facet along with a measured index profile is provided in Fig. 1a. The fiber consists of a nearly single moded core and an inner cladding that acts as guiding region for higher order modes up to $LP_{0,12}$ at 1 μm. The outer cladding extends to an outer diameter of 130 μm.

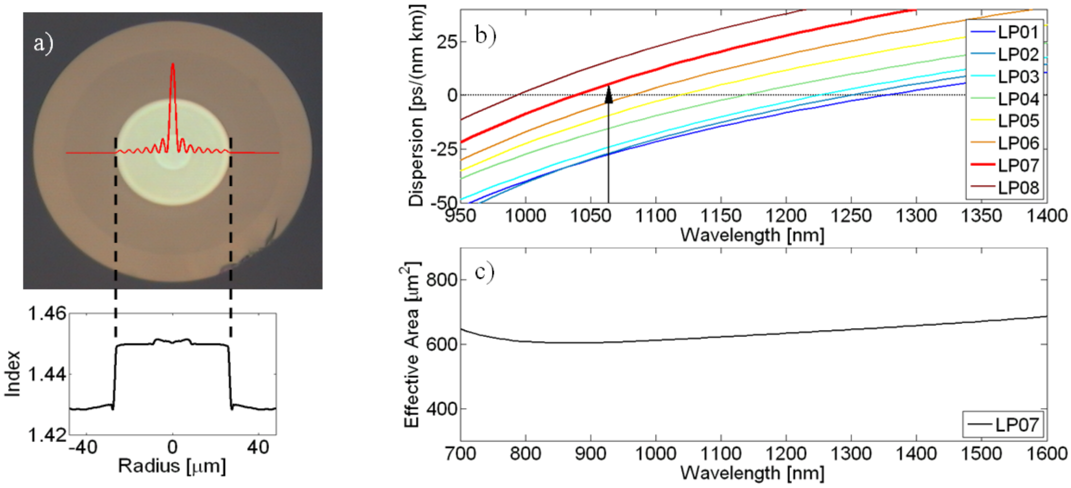

Fig. 1: a) End facet image (top) and index profile (bottom) of double clad fiber; $LP_{0,7}$ mode profile at 1 μm is overlaid on the facet image. b) Dispersion vs. λ for different modes; Arrow indicates the 1064.6 nm pump. c) A_{eff} vs. λ for the $LP_{0,7}$ mode.

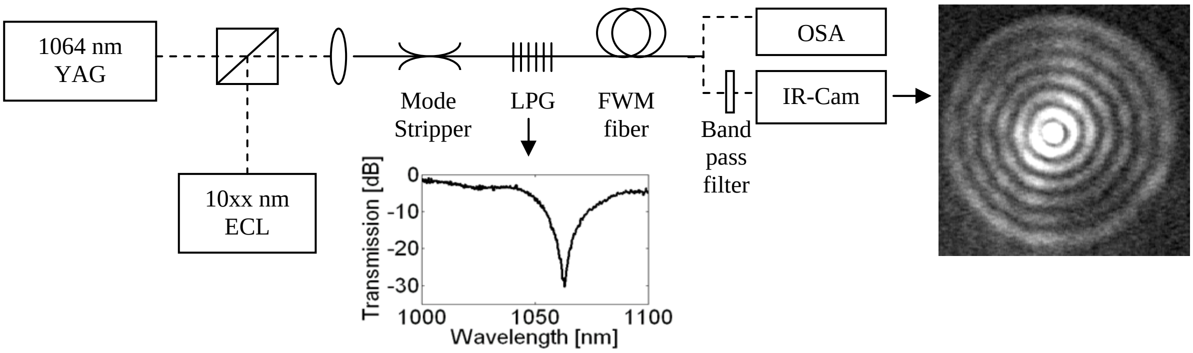

Fig. 2: Setup showing that a Nd:YAG pump and seed from an ECL are fed into the fiber and converted to the LP_{07} mode with an LPG. Insets show LPG spectrum, and mode image after 11 m of fiber propagation.

The simulated dispersion curves show that the ZDW decreases with increasing mode order, as shown in Fig. 1b. The first mode that experiences anomalous dispersion at 1064 nm is $LP_{0,7}$. This mode is used in the experiment to demonstrate FWM processes in this fiber.

Fig. 1c shows the A_{eff} of the $LP_{0,7}$ mode as a function of wavelength. The A_{eff} only changes by ~10 % over an octave spanning wavelength range, owing to strong confinement of the mode (which is also the fundamental reason we can achieve anomalous dispersion despite this mode's large A_{eff}). This ensures a high overlap integral over a large spectral range, enabling efficient nonlinear interactions over large bandwidths.

Experimental setup

The experimental setup for our demonstration is shown in Fig. 2. A Nd:YAG pump source generating 7 ns pulses at a 15 Hz rep rate is combined with the signal from a 1048 nm tunable external cavity laser (ECL) using a free space beam splitter. The two wavelengths are coupled into the double cladding FWM fiber with an aspheric lens (with the latter acting as a seed source for some of our experiments).

We employed a mode stripper that eliminated all HOMs in the fiber, thereby ensuring that only the $LP_{0,1}$ mode propagates. This is then followed by a long period grating (LPG) inscribed in the double-clad fiber, which converts light from the $LP_{0,1}$ to the $LP_{0,7}$ mode. The inset in Fig. 2 shows the measured spectrum of this LPG, revealing that, at the pump wavelength of 1064.6 nm, 30-dB conversion (99.9%) is achieved, resulting in the pump being launched in the LP_{07} mode of this fiber with exceptional mode purity.

The FWM process takes place in the remaining 11 meters of fiber, following the LPG, since light propagates over this length in a mode with anomalous dispersion. The output from this fiber is characterized via spectral measurements using an optical spectrum analyzer (operating in the pulsed mode, since our source had a low rep. rate: 15 Hz), and with a camera, to observe the output mode image (inset in Fig. 2 shows a measured camera image, illustrating a very high purity LP_{07} mode, as expected from the high mode conversion efficiency of our LPG).

Experimental results

The zero dispersion wavelength for the $LP_{0,7}$ mode is λ_{ZDW}=1038.4 nm, which means that this mode has anomalous dispersion at the pump wavelength of 1064.6 nm. The phase matching curve for the FWM process, where all interacting waves are in the same ($LP_{0,7}$) mode is shown in Fig. 3a. The horizontal lines in Fig. 3a delineate the spectral range over which FWM gain is obtained in the undepleted pump regime – thus, for the $LP_{0,7}$ mode of this fiber, we expect a gain bandwidth of 44 nm, extending from 1043 to 1087 nm. The dashed line's intersection with the phase matching curve (at 1048 and 1080 nm) indicate the wavelengths of maximum gain. Thus, when this fiber is pumped with a sufficiently high-energy source propagating in the anomalous-dispersion $LP_{0,7}$ mode, we expect a 44-nm wide spontaneous gain spectrum that peaks at 1048 and 1080 nm, respectively. Note that this is in direct analogy to the production of broadband modulation instability (MI) spectra in single-mode fibers when they are pumped in the anomalous dispersion regime.

Fig. 3b shows the spectrum for an input pump pulse energy of 30.4 μJ. Modulation instability peaks are evident on each side of the pump. The bandwidth of the gain region is close to the expected spectral range predicted by the phase matching conditions shown in Fig. 3a. The measured gain peaks are at 1049 and 1083 nm, respectively, which are once again close to the expected values. The asymmetry of the gain spectrum, and the fact that the spectral positions of the two gain peaks are not strictly symmetric

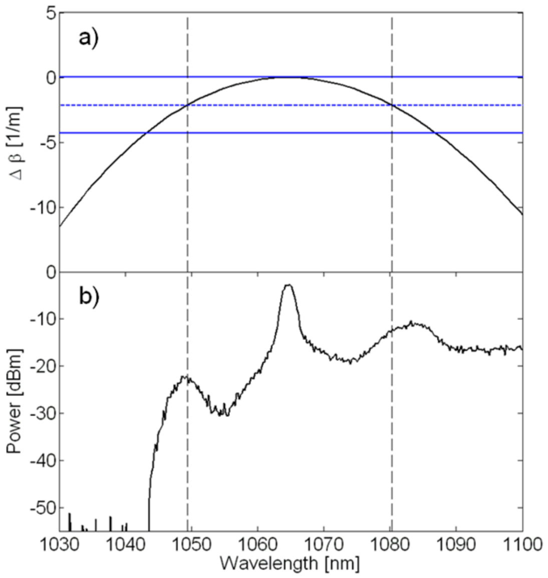

Fig. 3: (a) FWM Phase matching curves for the $LP_{0,7}$ mode. Maximal gain occurs at the intersection of the phase matching curve with the dotted line. (b) Output spectrum for pump pulse energy of 30.4 μJ. Note that the MI gain peaks approximately line up with maximal gain wavelength shown in (a).

around the pump wavelength is most likely due to stimulated Raman scattering (SRS), which is well known to distort MI gain spectra (since the blue-shifted anti-Stokes line and the 1064.6 nm pump serve as pumps for the red-shifted Stokes line).

Fig. 4 illustrates the influence of the addition of a narrowband seed at the anti-Stokes gain peak of the MI spectrum shown in Fig. 3. This seed, from a separate ECL, tuned to the MI gain peak wavelength of 1048 nm, is multiplexed into the fiber at the input, as shown in the schematic of Fig. 2. The broad bandwidth of the mode-converting LPG ensures that 65 % of the seed energy is also converted into the desired $LP_{0,7}$ mode. In addition to amplification of the signal and generation of an idler at 1080 nm, we also generate cascaded signal and idler lines at 1032 nm 1096 nm, respectively, showing the possibility of creating high-energy frequency combs by this process.

Current experiments were limited to 30-μJ energy levels due to constraints in coupling efficiency between a low beam quality free-space ND:YAG laser and our fiber. However, given the large A_{eff} (618 μm^2) of the $LP_{0,7}$ mode in this fiber, up to 0.54 mJ could have been coupled into this fiber before the onset of dielectric breakdown. In contrast, a PCF designed to achieve similar anomalous dispersion (and hence similar MI bandwidth) would have an A_{eff} of only 11.5 μm^2, and would have failed (due to dielectric bulk damage) at 45 μJ. Thus, an order of magnitude higher energy pulses can be used with the HOM fiber in comparison to PCF.

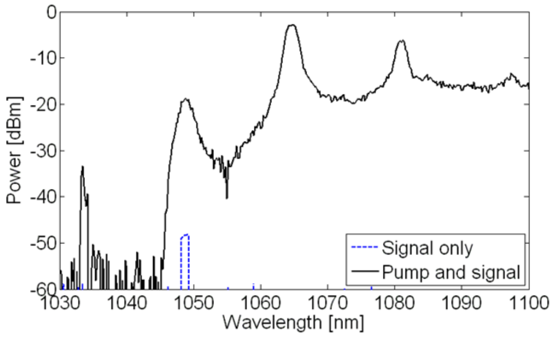

Fig. 4: Output spectrum for pump pulse energy of 30.4 μJ and a seed at 1048 nm. Solid line: only signal on; dashed line: both the signal and pump is on.

Conclusions

We have demonstrated, for the first time, to the best of our knowledge, modulation instability and multiple FWM Stokes and anti-Stokes lines in the 1 μm wavelength range in a large mode area fiber. The key enabler of this demonstration was operation in the $LP_{0,7}$ mode of a double-clad fiber, which has anomalous dispersion despite having a mode area of 618 μm^2 at 1064 nm. We employed pump energy levels of 30 μJ, limited by available pumps, but our fiber is capable of enabling scaling to 0.54 mJ pump pulse energies before the onset of dielectric breakdown. This represents a 12x increase in pulse energies at which parametric nonlinear processes could be exploited, compared to PCFs. Further improvement is possible by using even larger mode area HOM fibers, making this approach energy scalable and an attractive path way for creating ultra-high powered lasers, supercontinuum sources, and frequency combs, enabled by parametric, in-fiber nonlinearities.

Acknowledgements

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