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Nonlinear effects generation in non-adiabatically tapered fibres

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A B S T R A C T

Nonlinear effects are observed in a non-adiabatically tapered optical fibre. The designed structure allows for the introduction of self-phase modulation, which is observed through pulse breaking and spectral broadening, in approximately a centimetre of propagation using a commercial telecom laser. These devices are simple to fabricate and suitable to generate and control a variety of nonlinear effects in prac-tical applications because they do not experience short-term degradation as previously reported approaches. Experimental and theoretical results are obtained, showing a good agreement.

Keywords:
Nonlinear optics fibres
Fibre optics measurements
Optical processing

I. INTRODUCTION

Optical fibre is not only an excellent transmission medium but a highly useful element to implement multiple devices and function-alities. Doped fibres provide the necessary gain medium to build lasers while others types compensate for the dispersion of stan-dard fibre or increase light-matter interaction through tight con-finement of the optical field [1]. A lot of progress has been done recently towards the compact and controlled generation of nonlin-ear effects. It has been studied in microstructured fibres [2] while supercontinuum generation up to the ultraviolet has been reported using very particular types of optical fibres [3,4].

In this same direction, tapered fibres emerged as a simple way to modify the properties of optical fibres by reducing its cross-section [5]. They have been used for sensing [6], supercontinuum generation [7] and efficient coupling to waveguides and micro-resonators [8,9], among others.

Tapered fibres are often classified as adiabatic or non-adiabatic according to its transition length. In the first case, the transition is gradual enough to avoid any coupling between the fundamental mode and higher order modes. They are the best choice for appli-cations that require different degrees of confinement such as super-continuum generation [7] or evanescent field coupling [9]. On the other hand, in non-adiabatic tapers the waveguide cross-section changes so abruptly that the energy of the fundamental mode splits into several modes that propagate before interfering at the output of the device. Applications of non-adiabatic tapers include tunable optical filtering [10] and different types of sensing [6].

In this work, we demonstrate nonlinear generation using non-adiabatically tapered fibres for the first time to our knowledge. Nonlinear effects intensify when compared to those taking place in a standard fibre due to dispersion tailoring and to the increased power density obtained when coupling light from the fundamental core mode of a stretched piece of standard single-mode fibre into higher-order cladding modes. Previous approaches that rely on adiabatic tapers with micron or submicron diameters [7,11] are able to introduce a large amount of nonlinear effects even under low optical power excitation, although tapers with such small diameters are degraded and even destroyed in a few days or hours. Our device is not as efficient but can be used in a wide range of practical applications because it does not suffer from fast degrada-tion due to its relatively large diameter and presents an efficiency several times larger than that of standard fibre [12]. The periodic transference function of the device, which can be tuned through optimization of its geometry, makes it especially useful for applica-tions such as wavelength-division multiplexed networks and opti-cal comb generation, where a large number of spectrally spaced components are required. Because the approach relies on the stretching of a piece of standard fibre we believe this is one of the simplest solutions that can be found to generate nonlinear effects in fibre-based systems.

II. PRINCIPLE OF OPERATION

A tapered fibre can be depicted as a waist of length L_w and diameter q between two coupling regions of length T_t, as shown in Fig. 1. When the fibre-to-waist transition is abrupt, the energy carried by the fundamental mode splits into different modes. For the structures considered in this paper two modes, the fundamen-tal cladding mode and a higher order cladding mode, gather most of the optical power. These modes couple back into the fundamen-tal mode of the standard fibre along the second transition. Time-delayed replicas of the input optical field will be obtained at the output of the tapered fibre because of the different propagating modes indexes. When most of the injected power is split into two modes their interference results in a sinusoidal fringe pattern in the frequency domain.

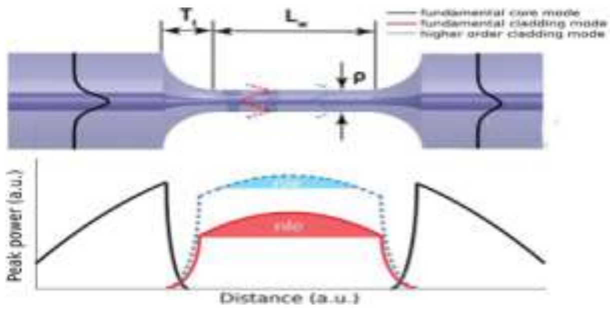

Fig. 1. Power evolution of the main modes existing in the taper for a propagating optical pulse. Shaded areas depicted with nle show peak power values exceeding the nonlinear power threshold for each cladding mode. The modes sketched represent a 2-dimensional section of their corresponding intensity profile and appear at different positions along the waist to illustrate their different effective propagation indexes.

Consider now a dispersion pre-compensated optical pulse prop-agating through the fibre. It narrows during its propagation and, for powers exceeding a certain value, nonlinear effects such as self-phase modulation become noticeable [13]. The nonlinear power threshold can be drastically decreased through the tapering of the standard fibre at the maximum optical intensity point as long as the reduction in the effective area of the modes compen-sates for the losses introduced by the power splitting [13]. This mechanism allows for power-efficient generation of nonlinear effects using standard optical fibre. As demonstrated here, the fun-damental cladding mode experiences nonlinear propagation for lower peak power values because its high spatial confinement results in reduced nonlinear power thresholds.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental setup is shown in Fig. 2. It consists of a fem-tosecond fibre laser (FemtoFErb from Toptica Photonics) which emits 100-fs optical pulses at a repetition rate of 100 MHz with an average power of 100 mW. A piece of dispersion compensating fibre (from OFS) is used to pre-compensate for the second-order dispersion of 10 m of standard fibre (SMF-28e+ from Corning). Dis-persion pre-compensation was carried out so non-linear effects could not be observed before the tapering of the fibre. At the end of the link, the optical fibre was tapered by reducing its transversal section through controlled heating and mechanical pulling along its propagation axis [5].

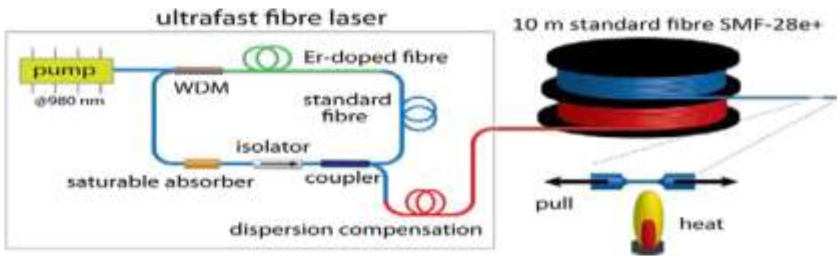

Fig. 2. Experimental setup used in nonlinear generation. The end of the fibre is tapered through a heating and pulling process.

For our design, the transition regions of the tapered fibre pre-sent an exponential profile with $T_t = 1$ mm, while the waist length and diameter are $L_w = 13$ mm and q = 18 lm, respectively. The taper was large enough to be visible using a standard camera, as shown in Fig. 3, where its transference function, measured using a tunable laser and a power meter, is also included. The taper has 3 dB insertion losses and a free spectral range of approximately 6 nm. Its transference function is practically sinusoidal, as expected since two modes gather most of the energy. Small devia-tions from a pure sinusoidal shape are due to the contact between the tapered fibre and its support surface, which modifies the response of the device [14]. In these structures, the spectral fringe period depends mainly on the waist length, making available robust tapered fibres with fringe periods between a few nm and 200 nm. This would be hardly attainable using other technologies.

The nonlinear Schrödinger equation was solved using the split-step Fourier method [13] to simulate pulse propagation through the fibre link. A 100-fs sech2 optical pulse was considered in the simulation in order to realize an accurately comparison with the experiments. Simulations include second- and third-order disper-sion, losses and different nonlinear effects such as self-phase mod-ulation. Typical parameter values were used for the standard and dispersion compensation fibres. In addition, effective areas and propagation indexes of the different taper cross sections were cal- culated using commercial photonics simulation software. Values of 1.4475 and 1.444 are considered for the core and cladding materi-als, respectively. The nonlinear index is 2.6 10–20 m^2/W. For the standard fibre, we consider a group velocity dispersion (GVD) of 17 ps/nm km and a dispersion slope of 0.13 ps/nm^2 km. These val-ues become 50 ps/nm km and 0.1 ps/nm^2 km in the waist of the taper. These values are referred to a wavelength of 1550 nm. The effective mode area of the core mode of the standard fibre is 80 lm^2, which is reduced to half this amount for the cladding modes. The two cladding modes that propagate through the waist have effective refractive indexes of 1.4444 and 1.4214, respec-tively. Fig. 4 shows the theoretical results of the nonlinear Schrödinger equation in both time and spectrum domains. Chirped pulse distribution considers the fibre link without the tapered fibre. The peak power can be increased up to some tens of kW with no evidence of nonlinear effects thanks to the pre-chirping of the pulses. After including the tapered fibre in the simulator, two pulses with their associated fringed spectrum can be observed, where the spectral distance between maximums or minimums is the same than that exhibited in the transference function of Fig. 3. As can be seen, nonlinear generation is not appreciable for input peak power values up to 5 kW. This value agrees well with the theoretical results, which for our waist diameter and length estimates that nonlinear effects should become appreciable for peak powers above 7 kW [13]. After injecting pulses with a peak power of 10 kW, nonlinear effects become noticeable. Typical fea-tures of self-phase modulation such as pulse breaking and spectral widening can be clearly appreciated in the time and spectrum domains, Fig. 4(a) and (b), respectively.

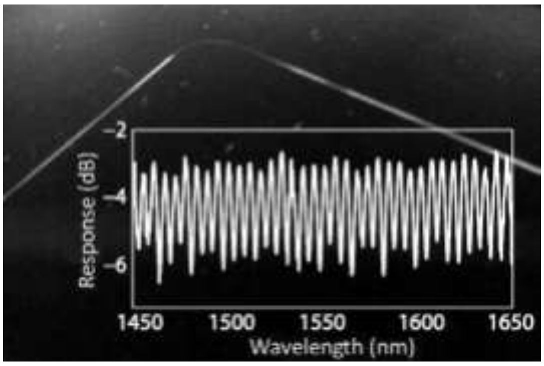

Fig. 3. Photograph of the fabricated tapered fibre and its optical characterization by means of a tunable laser and a power meter.

Fig. 5 shows the experimental results. Chirped pulse distribu-tion allows for linear delivery of the optical pulses. After the fibre

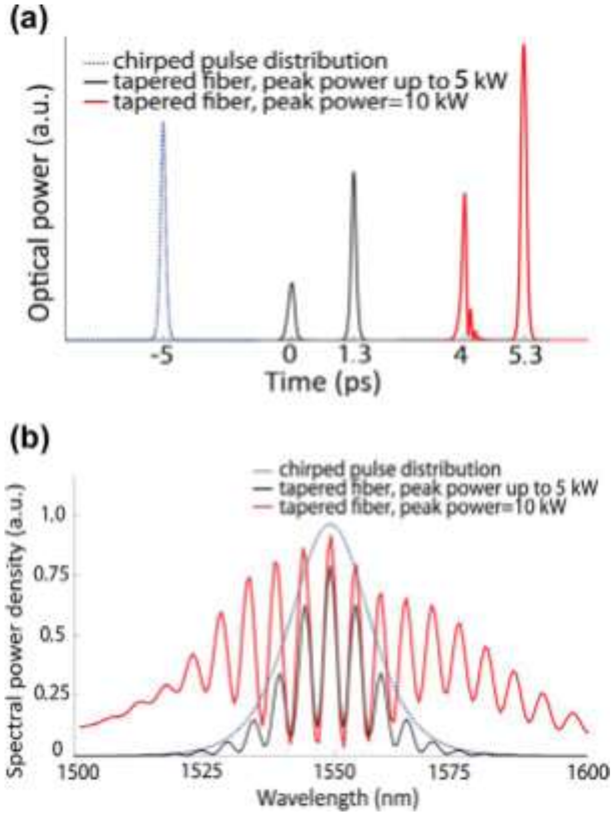

Fig. 4. Numerical solution of the nonlinear Schrödinger equation for a pulse that propagates through the fibre link, (a) Time-domain results and (b) Spectrum- domain results.

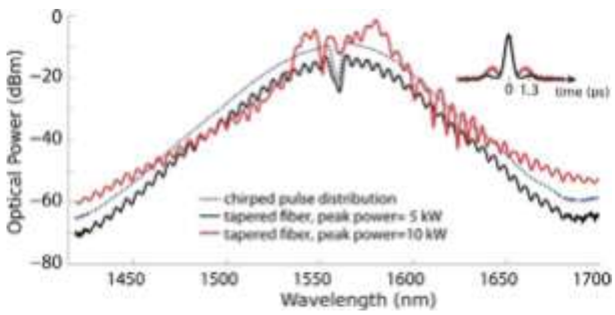

Fig. 5. Spectra showing linear and nonlinear operation of the taper. Corresponding optical intensity autocorrelation traces are shown in the upper right corner.

tapering process, the resulting spectrum for peak powers below the nonlinear threshold corresponds with the filtered optical source. By using 10 kW pulses, nonlinear effects, mainly self-phase modulation, reshape the spectrum and increase the visibility of some fringes. The inset in Fig. 5 shows the obtained autocorre-lation intensity traces. As can be observed, nonlinear effects intro-duce a change in the amplitude ratio between the peaks. Although sub-pulses originating from self-phase modulation cannot be resolved using our intensity autocorrelator, the reduction in the relative delay between main and secondary peaks suggests pulse breaking. Differences between the experiments and simulations arise due to differences between the real and estimated parameters along with the limited resolution of the experiments. However, the main features that indicate nonlinear generation such as asymmet-ric spectrum expansion and variable fringe visibility are shown in both cases while appearing at the same optical power levels. Because the experiments aimed to find the power threshold for nonlinear generation, the expansion of the spectrum is not notice-able for its central components, although it is visible for those around 1450 nm and 1650 nm. The asymmetry observed in the output response is due to the chirp imposed on the input pulse when the propagating pulse experiences self-phase modulation [15]. The obtained results show that the required power to gener-ate nonlinear effects is reduced by a factor of 8 when compared with the power levels that would be required using standard opti-cal fibre.

IV. CONCLUSION

In this work, nonlinear generation through the self-phase mod-ulation effect is proposed and demonstrated using non-adiabatically tapered fibres. The fabricated device considerably reduces the minimum optical power required to generate nonlin-ear effects as demonstrated through simulations and experiments. It is simple to fabricate, made of standard fibre and robust enough to be useful in practical applications where previous approaches based on adiabatic tapers with micron or submicron radii are not suitable due to their short lifetimes. Because of its interfero-metric nature and tunable spectral period, this device should be useful in several applications, including wavelength generation in wavelength-division multiplexing systems.

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Fig. 4. Numerical solution of the nonlinear Schrödinger equation for a pulse that propagates through the fibre link, (a) Time-domain results and (b) Spectrum-domain results.

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