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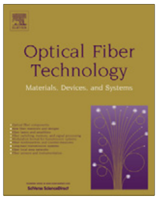

Invited Papers

Supercontinuum generation in non-silica fibers

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ABSTRACT

The development of super continuum sources is driven by the requirements of a wide range of emerging applications. This paper points out how non-silica fibers are of benefit not only because their broad mid-IR transparency enables continuum generation in the 2–5 μm region but also since the high intrinsic nonlinearity of the glasses reduces the power-threshold for devices at wavelengths below 2 μm. For these glasses, the material zero-dispersion wavelength is typically shifted to long wavelengths compared to silica so dispersion tailoring is key to creating sources based on practical, near-IR, solid state pump lasers. We show how modeling work has produced fiber designs that provide flattened dispersion profiles with high nonlinearity coefficients and zero-dispersion wavelengths in the near-IR. Building on this flexibility, modeling of the pulse dynamics then demonstrates how coherent mid-IR supercontinuum sources could be developed. We also show the importance of the second zero-dispersion wavelength using bismuth fibers as an example. Nonlinear mode-coupling is shown to be a factor in larger core fibers for high-power applications. Demonstrations of supercontinuum in microstructured tellurite fibers, all-solid lead–silicate (SF57) fibers and in bismuth fibers and tapers are then reported to show what has been achieved experimentally using a range of materials and fiber geometries.

1. Introduction

Supercontinuum (SC) is now widely used in analytical spectroscopy and tomographic imaging applications across the visible and near IR range [1–4]. Moving to longer wavelengths, continuum generation in the mid-IR is an emerging research area driven by the large number of potential applications that require moderate to high brightness sources with wide bandwidths that are not adequately served by thermal emitters or quantum-cascade lasers. While optical parametric oscillators and amplifiers (OPO/OPAs) [5,6] have been used successfully, they are often complex and costly components that require high initial investment and maintenance. Fiber based sources using well established high power fiber and solid state near-IR laser sources are therefore attractive [7–9].

Beyond a wavelength of 2 μm, due to the onset of losses in silica, it is often necessary to use non-silica glasses. Research on non-silica fibers has been ongoing for many years for sensing and imaging applications and for CO_2 laser beam delivery, where their low mid-IR loss is critical. However it is not only for long wavelength applications that these glasses provide potential advantages. The nonlinear properties of these glasses can enhance supercontinuum generation as they can have intrinsic nonlinearities ~10× to 100× that of silica [9]. The use of microstructured optical fiber (MOF) technology, and tapering, provides a further enhancement to the nonlinearity and enables control over the dispersion profile for both telecommunications switching [10–14], and for supercontinuum generation [15].

Dispersion control is critical in that it allows greater flexibility in terms of choice of SC pump wavelength since the zero-dispersion wavelengths (ZDWs) of these materials are generally longer than for silica, as illustrated in previous work [7,9] and the material dispersion curves for bismuth and tellurite glasses are shown in later sections of this paper. The waveguide dispersion of the fibers is therefore used to improve their compatibility with near-IR pump lasers, and in particular the Yb band at 1.05 μm, the Er band at 1.55 μm and the Tm/Ho band at 1.7–2.2 μm. In practice, dispersion tailoring is achieved by using high index contrast between the core and cladding either using fiber tapers, air holes in microstructured fibers or high-index-contrast glasses in the core and cladding of the fiber.

The ability to tailor the fiber dispersion profile is a theme underlying all of our work and one which cuts across all the glasses and fiber designs. One of the primary advantages of MOF technology is that it provides for an enormous amount of design flexibility. The development of advanced numerical modeling tools has been

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essential for understanding and exploiting the range of possible structures. Following extensive research with silica MOF, tools for calculating the properties of a given structure (idealized, or based on SEM images of real fibers), are now well developed. The main challenge now is to find the best ways of exploiting these tools for investigating the large parameter space. In this paper we briefly review the modeling techniques used for non-silica fiber design and highlight our latest work on all solid lead–silicate fibers [16].

Although dispersion tailoring can enable pump lasers to be coupled either in the normal or in the anomalous dispersion regions of fibers, the resulting performance in terms of spectral extent and coherence characteristics of the supercontinuum also depends on the detailed broadband dispersion properties. At the forefront of silica fiber based continuum research is the use of microstructured fibers to provide a coherent spectrally broadened output that can be subsequently recompressed to pulses of one or two optical cycles. This also provides the opportunity to transfer a frequency comb from a seed laser to new wavelengths for metrology [17] and spectroscopy [18]. In a pulsed system, the average power is proportional to the repetition rate, so when using high repetition rate sources that provide widely spaced comb lines the average power will tend to increase which would increase the complexity of the system. However, if the pulse energy required for continuum generation can be reduced this problem is avoided. Increasing the nonlinearity of the fiber using soft-glasses is one option achieving this and we have used our experience with silica fibers [19–22] to consider the possibility of producing a coherent mid-IR continuum from a tellurite fiber. The broad mid-IR transparency window of this glass should enable the comb to be transferred across the mid-IR for use as a source for spectroscopy. We also note the possibility of producing broadband low-coherence supercontinuum in the mid-IR using fibers with two ZDWs. Using the example of a bismuth fiber, we show modeling results illustrating the importance of the pump wavelength in relation to the upper of those ZDWs. A further aspect of our work is power scaling in large core fibers and we report the first full numerical simulations in multimode non-silica fiber to demonstrate the possible influence of nonlinear mode-coupling which may occur when moving to larger fiber structures.

This is a relatively new research area and the technology is progressing rapidly with a variety of non-silica glasses. Recent work with fluoride fibers includes that by Kulkarni et al. which used a nano-second Erbium doped fiber amplifier chain reported earlier in Refs. [23,24] combined with a section of Thulium doped fiber to boost the long wavelength supercontinuum power [25]. The maximum wavelength increased by 270 nm and a 2.5 times improved efficiency of the energy transfer from the pump wavelength to the wavelength range above 3.8 μm was achieved. Subsequent work with fluoride fibers includes the consideration of high power actively mode-locked Tm fiber pump lasers to seed at 1.9 μm instead of at 1.55 μm [26–28]. This complements the work on tellurite [29] and fluoride glass fibers that have been developed for both Raman and rare-earth doped telecommunication amplifiers to provide gain across greater transmission windows, see [30,31].

We also note that chalcogenide fibers have been studied for mid-IR continuum generation as they have even higher intrinsic nonlinearity than oxide based glasses and a wider transparency window to >8 μm. Examples of reported results include experimental work on continuum by Shaw et al. [32], which was later complemented by modeling work aiming to optimize the results [33–36]. In the near-IR, telecommunications driven research used a chalcogenide fiber tapered to sub-wavelength dimensions and pumped in the femtosecond regime achieved low threshold energy continuum generation [37]. However, because the dispersion profile was not optimized for the telecommunications band, the continuum was not flattened. A small suspended-core chalcogenide fiber design has also been proposed theoretically for wavelength conversion starting from a 1.8 to 2.1 μm Tm fiber laser and targeting a source output at 4.5 μm as a potentially useful source in the second transparency window of the earth's atmosphere [38]. This complements the work on tellurite [29,39] and fluoride glass fibers that have been developed for both Raman and rare-earth doped telecommunication amplifiers to provide gain across greater transmission windows, see [30,31].

In addition to the numerical simulations described above, this paper provides a broad overview of our experimental work with a variety of soft glasses including tellurite, lead–silicate and bismuth oxide. We show how small-core tellurite fibers can generate mid-IR continuum pumped with Yb-fiber sources at 1.05 μm by Raman (Stokes) shifted power transfer across the ZDW. Supercontinuum in very large mode tellurite microstructured fiber is reviewed due to the potential for single mode power scaling by employing a weakly guiding design [40]. We then report how high precision dispersion profile control in a lead–silicate fiber has enabled low threshold continuum generation and phase sensitive amplification [41–43]. The fiber provided a unique combination of high nonlinearity (820 $W^{-1}\,km^{-1}$) and a flat near-zero dispersion profile. Work in bismuth fibers for long wavelength continuum beyond 2 μm and in bismuth tapers for low threshold continuum in the telecommunications wavelength band is reviewed to show the flexibility of post-processing the fibers to optimize the dispersion profile.

The paper is structured as follows. Section 2 reports how our modeling work has led to advanced fiber designs, the prospect of creating both high-and low-coherence mid-IR continua and finally the ability to study multimode nonlinear interactions with high precision. Then Sections 3–5 report our experimental work on tellurite, lead–silicate and bismuth fibers, respectively. Finally, Section 6 provides a summary and conclusion.

2. Advanced techniques for modeling fiber designs, pulse propagation dynamics and for solving the multimode nonlinear Schrödinger equation

2.1. Introduction

Since the ability to understand and predict the modal confinement and dispersion in non-silica fibers is a critical aspect of research in the field, an array of modeling techniques has been developed to study the possible fiber designs. These are summarized briefly in Section 2.2 before moving on to more recent simulations that scan through design-space to optimize fibers for particular applications. The example of an all solid lead–silicate W-type is shown in detail.

To develop an understanding of the pulse-propagation it is necessary to use tools to solve the generalized nonlinear Schrödinger equation (GNLSE) [44]. In this section we explore an example of how the latest tools are driving advanced fiber research. In Section 2.3 we report how in future a coherent mid-IR continuum could be generated from a tellurite fiber pumped by a Tm/Ho fiber laser at a wavelength of 2 μm. Then to investigate what an incoherent broadband source for mid-IR SCG could produce using bismuth microstructured optical fibers (MOFs) with two ZDWs, a numerical modeling survey in Section 2.4 was performed considering a range of fiber parameters (see Refs. [7,9,45]). This is a dynamic research area and examples of work by other groups in different glass materials can be found in the following Refs. [33,34,38,46,47].

A comparatively new and unexplored area is the modeling of pulse propagation in *multimode* optical fibers which may be necessary for large-mode area fibers developed for high-power applica-