Tampere University

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MID-INFRARED SUPERCONTINUUM GENERATION FOR SPECTROSCOPIC APPLICATIONS

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ABSTRACT

Tuuli Nissinen: Mid-Infrared Supercontinuum Generation for Spectroscopic Applications
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Spectroscopy in the mid-infrared spectral region has several applications ranging from gas sensing to optical coherence tomography and medical applications because of unique molecular absorption signatures. Current light sources used for applications in spectroscopy are not suitable for all cases because of numerous parameters such as narrow bandwidth or low power levels. Using supercontinuum generation in nonlinear optical fibers is a field of interest as the laser sources can be made compact and cost effective but still have broad bandwidth towards the mid-infrared with high coherence properties and high power.

Creating an all-fiber supercontinuum into the mid-infrared requires the use of soft-glass fibers that have transmission window extending to the desired region. Silica fibers are highly studied due to their good availability and transmission to the near-infrared region, but reaching the mid-infrared spectral region is not possible due to material absorption above 2500 nm. Soft-glass fibers with lower damage threshold but higher nonlinearity and transmission are cascaded with the silica in order to create supercontinuum extending to the mid-infrared, as demonstrated in this thesis.

This thesis discusses current supercontinuum-based commercial light sources in the mid-infrared. They are based on using single-mode optical fibers with a lower damage threshold and this limits the achieved power spectral density crucial for applications such as remote sensing or molecular spectroscopy. One must seek for solutions allowing for the increase of the supercontinuum source power output. This work investigates the possibility of using multimode fibers with larger core size, and therefore, a higher damage threshold, for supercontinuum generation light sources in the mid-infrared.

The physical phenomena behind supercontinuum generation are introduced in this thesis. Additionally, basic fiber properties are shown focusing on different refractive index profiles. The experimental part demonstrates supercontinuum generation in a cascade of step-index multimode silica and soft glass fibers with a nanosecond fiber laser. Different combinations of silica and soft glass fibers were used to optimize broadening, power levels and clean transverse intensity distribution. With a multimode step-index silica and indium(III)fluoride, the generated supercontinuum spans from 730 nm to 3000 nm with coupling efficiency of 70 %, extending in the mid-infrared region.

Keywords: supercontinuum, multimode fiber, mid-infrared spectroscopy, gas spectroscopy

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TIIVISTELMÄ

Tuuli Nissinen: Superjatkumon generointi keski-infrapuna-alueella spektroskopisiin sovelluksiin
Kandidaatintyö
Tampereen yliopisto
Teknis-luonnontieteellinen
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Keski-infrapuna-alueen spektroskopialla on useita sovelluskohteita kaasujen analysoinnista valokerroskuvaukseen sekä lääketieteellisiin sovelluksiin molekyylien absorptiopiikkien vuoksi. Nykyiset sovelluksissa käytettävät valonlähteet eivät ole soveltuvia kaikissa tapauksissa eri parametrien, kuten kapean aallonpituuskaistan tai matalan tehon, vuoksi. Optisissa kuiduissa luotu superjatkumo on kiinnostava vaihtoehto valonlähteenä kompaktiuden ja kustannustehokkuuden takia, silti saavuttaen laajan aallonpituusalueen keski-infrapuna-alueelle korkean koherenssin ja suuren tehon lisäksi.

Täysin kuiduista luotu superjatkumo keski-infrapuna-alueelle vaatii pehmeälasikuitujen käyttöä, sillä niiden transmissioikkuna ulottuu halutulle alueelle. Piidioksidi- eli silikakuidut ovat laajasti tutkittuja niiden hyvän saatavuuden sekä transmission lähi-infrapuna-alueelle vuoksi. Keski-infrapuna-alueen saavuttaminen käyttäen silikakuituja ei ole mahdollista materiaaliabsorption vuoksi. Pehmeälasikuiduilla on matalampi vahingoittumiskynnys, mutta korkeampi epälineaarisuus sekä transmissio. Silikakuidun kanssa luodun kaskadin avulla saadaan luotua superjatkumo, joka ulottuu keski-infrapuna-alueelle. Kyseinen tutkimusjärjestely esitellään tässä opinnäytetyössä.

Opinnäytetyö esittelee nykyisiä markkinoilla olevia superjatkumopohjaisia valonlähteitä keski-infrapuna-alueella. Nämä lähteet käyttävät superjatkumon luomiseen yksimuotokuituja, joilla on matalampi vahingoittumiskynnys. Tämä rajoittaa saavutettua tehospektritiheyttä, joka on ratkaisevan tärkeä tiettyihin sovelluksiin, kuten kaukokartoitukseen tai molekyylispektroskopiaan. Täytyy siis etsiä ratkaisuja, jotka sallivat superjatkumolähteelle suuremman tehon. Opinnäytetyön kokeellisessa osassa tutkitaan monimuotokuituja, joilla on suurempi ydin sekä täten korkeampi vahingoittumiskynnys, superjatkumovalonlähteen luomiseksi keski-infrapuna-alueelle.

Tässä opinnäytetyössä esitellään superjatkumon fysikaalinen tausta. Lisäksi kuitujen perusominaisuudet käsitellään keskittyen erityisesti taitekerroinprofiileihin. Työn kokeellinen osa tutkii superjatkumon luomista monimuotokuiduissa, asettaen silika- ja pehmeälasikuidut sarjaan käyttäen nanosekuntilaseria. Mittaukset suoritettiin erilaisilla silika- ja pehmeälasikuitujen yhdistelmillä optimoiden aallonpituusspektrin leveyttä, tehoa sekä puhdasta intensiteettijakaumaa. Käyttäen askelindeksitaitekertoimista monimuotoista silikakuitua ja indium(III)fluoridikuitua, luotu superjatkumo käsittää aallonpituusalueen 730 nm–3000 nm liitoshyötysuhteella 70 %, levittäytyen keski-infrapuna-alueelle.

Avainsanat: superjatkumo, monimuotokuitu, keski-infrapuna-alueen spektroskopia, kaasuspektroskopia

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1. INTRODUCTION

Supercontinuum (SC) generation is a series of complex nonlinear processes that has gained interest in a wide range of applications, including spectroscopy, precision metrology, remote sensing and high-resolution imaging. First discovered using bulk glass in 1970 [1], the phenomenon has been widely researched because of its unique characteristics.

The physical background of supercontinuum generation is complex and different nonlinear phenomena affect the generation process. Using optical fibers to create supercontinuum is specifically interesting because the light source can be compact and have high power levels that are needed in some applications.

This thesis discusses current spectroscopic applications in mid-infrared supercontinuum lasers. The mid-infrared region is of major interest because of absorption signatures of most molecules. With spectroscopic measurements, those molecules can be detected using a wide-bandwidth light source efficiently and with a low footprint. Light sources reaching the mid-infrared region are commercially available, but lack in different areas critical for some applications. Creating an all-fiber supercontinuum source reaching the mid-infrared spectral region is of significant interest because a whole new range of applications in the molecular fingerprint region will be enabled.

Chapter 2 introduces the basics of supercontinuum generation and nonlinear physical phenomena behind it, focusing on using optical fibers as waveguides. In addition, the refractive index profiles of an optical fiber are considered. The current state of the art of mid-infrared light sources and their applications is discussed in chapter 3. The main experiments of cascading silica and soft glass fibers on creating supercontinuum into the mid-infrared spectral region are introduced in chapter 4. Lastly, conclusion of the results and further work proposals are shown on chapter 5.

2. SUPERCONTINUUM GENERATION

Supercontinuum (SC) generation refers to a cascade of nonlinear processes experienced by originally narrowband light source to result in spectral broadening creating new frequency components. The phenomenon was first reported in 1970 using bulk glass [1], but supercontinuum can be created in other types of nonlinear materials as well.

SC generation process highly depends on the laser light and material used. Both continuous-wave laser and pulsed laser can be used to generate supercontinuum. Nonlinear dynamics scales with the peak power and therefore short and intense pulses of light allows for more efficient SC generation [2]. Different kind of nonlinear effects may occur depending on the material properties. Typically SC is generated in optical fibers that have a waveguide structure that allows for long interaction length and efficient SC generation.

2.1 Physical background

Supercontinuum generation is based on a series of nonlinear dynamics that are briefly introduced in this chapter.

2.1.1 Dispersion

Dispersion refers frequency-dependence of the refractive index when light propagates in a material. The total dispersion includes both the waveguide and material dispersion.

When white light is guided through a prism, its wavelength components separate spatially and one can see the spectrum of visible light, a rainbow of colours. This is a good example for material dispersion. Material dispersion refers to the dependence of the refractive index of the material to the wavelength of the light guided through. It is caused by an electromagnetic wave interacting with the electrons of the material [2].

Another mode of dispersion is waveguide dispersion that needs to be taken into consideration when light is propagating through a waveguide. Waveguide dispersion arises from the geometry of the waveguide used. It is caused by wavelength-dependent solutions for the modes (electric field distributions) spatially. This causes shorter wavelengths to propagate closer to the core of the fiber and longer wavelengths extend to the cladding of an optical fiber. [2]

Group velocity dispersion (GVD) is responsible for broadening light pulses temporally because the propagation speed of different wavelengths differ. A Taylor series can be used to represent the mode-propagation constant $\beta(\omega)$ that describes the propagation of different wavelengths in an optical fiber. In the series, the term β_2 is the corresponding parameter to GVD and using it temporal broadening can be calculated. [2]

Depending on the sign of the GVD parameter, different kind of dispersion occurs. Normal dispersion is experienced when $\beta_2 > 0$ and shorter wavelengths propagate faster, and for anomalous dispersion ($\beta_2 < 0$), the opposite occurs. Zero dispersion wavelength (ZDW) is the wavelength where the GVD parameter is null. This is an important parameter when discussing SC generation, because different nonlinear effects arise in when the pump wavelength is in different dispersion regimes. Fibers can be manufactured in a way to shift the ZDW in the wavelength region of interest and where attenuation is minimum. [2] In order to achieve a broad spectrum, the pump wavelength needs to be on the anomalous dispersion region close to the ZDW of the optical fiber.

2.1.2 Nonlinear fiber optics

Nonlinear optics is a branch of physics that is centered on nonlinear materials and high-intensity electromagnetic waves for modifying optical properties.

To understand nonlinear effects, polarization $\widetilde{P}(t)$ which is the dipole moment per unit volume needs to be further considered. In a typical linear model, electrons are considered as harmonic oscillators and their polarization and the strength of the electric field are proportional as

$$\widetilde{P}(t) = \epsilon_0 \chi^{(1)} \widetilde{E}(t), \tag{2.1}$$

where $\chi^{[1]}$ is the linear susceptibility and ϵ_0 the permittivity in a vacuum. When considering nonlinear optics, the polarization equation needs higher order terms and it can be expanded into a series

$$\widetilde{P}(t) = \epsilon_0[\chi^{(1)} \widetilde{E}(t) + \chi^{(2)} \widetilde{E}^2(t) + \chi^{(2)} \widetilde{E}^2(t) + \ldots], \tag{2.2}$$

where $\chi^{(2)}$ and $\chi^{(3)}$ are second- and third-order nonlinear optical susceptibilities. The polarization field $\widetilde{P}(t)$ and the electric field $\widetilde{E}(t)$ are scalars in equations 2.1 and 2.2. If the vector nature is taken into consideration, the susceptibilities become tensors with ranks $n + 1$, where n is the original order of the susceptibility. [3]

Optical Kerr effect

The Kerr effect or the quadratic electro-optic effect can be defined as the change of the refractive index of the material because of electric field interactions. The change of the refractive index Δn depends quadratically on the strength of the electric field. [3]

When discussing the optical Kerr effect, it refers to using a high-intensity pump laser propagating through a nonlinear medium. The electric field of a laser pulse induces the effect instead of using an external field. This causes the refractive index of the material to change proportionally to the time-dependent intensity of the electric field $I(t)$ by

$$\Delta n = n_2 I(t), \tag{2.3}$$

where n_2 is the nonlinear refractive index dependant of the third-order susceptibility $\chi^{(3)}$. The nonlinear refractive index is characteristic to each material. [2]

Self-phase and cross-phase modulation

Self-phase modulation (SPM) is based on the optical Kerr effect. Due to the high-intensity optical pulse propagating in the material, the refractive index of the material changes and a phase change occurs to the propagating pulse. This type of phase change is called a chirp and it indicates that the optical frequency of the pulse is time-dependent. Chirps create new frequency components symmetrically around the center frequency and thus broaden the spectrum. [2]

If there are more than one propagating optical pulse, the optical fields of the pulses of different wavelengths can interact with each other. This phenomena is called cross-phase modulation (XPM), and it is similar to SPM. In difference to the symmetric broadening of SPM, XPM can have asymmetric broadening around the central frequency. [2]

Four-wave mixing and modulational instability

Four-wave mixing (FWM) is used for a variety of applications in supercontinuum generation. As the name suggests, the phenomenon consists of four optical waves as well as a third-order susceptibility $\chi^{(3)}$. Matching the optical wave frequencies and fiber parameters is significant. If there is no phase matching, sufficient broadening is not reached. The phase matching condition depends on energy and momentum conservation. [2]

If the wavelength of an optical pulse lies in the anomalous dispersion regime and the phase matching condition is achieved, FWM causes new sidebands to be amplified symmetrically around the central frequency. In a special case where two pump beams have the same frequency, the phenomena is called degenerate FWM and two photons with symmetric spectral sidebands are created. [2]

In a regime where both SPM and XPM affect the FWM process, the phenomenon is called modulational instability (MI). This process is generally described in the time-domain while FWM is usually described in the frequency-domain. [2]

Solitons

In the normal dispersion regime, pulse broadening is achieved as the combined effect of dispersion and SPM. However, these effects can balance each other in the anomalous dispersion regime and create optical solitons. Fundamental or first-order solitons $(N = 1)$ do not change their shape spectrally or temporally when propagating through a material, but the shape of higher order solitons $(N > 1)$ evolutes periodically both spectrally and temporally. [2]

Generally, solitons are the solutions for the nonlinear Schrödinger equation (NLSE) that governs the propagation of light in a nonlinear medium. Solitons can be modelled with a hyperbolic secant function. For a soliton to be excited in an optical fiber, the input pulse must have a profile at $z = 0$ of

$$A(z = 0, t) = \sqrt{P_0}\,\mathrm{sech}\,\frac{t}{\tau_0}, \tag{2.4}$$

where P_0 is the peak power and τ_0 width of the soliton. The width can also be shown as the full width at half maximum, $\tau_0 = \tau_{FWHM}/1.763$. In order to excite a soliton in an optical fiber, the input pulse must have an exact relation with the amplitude and width. [4]

Stimulated Raman scattering

Raman scattering is an inelastic scattering process that can be described classically as the interaction of an optical field with a material. The interaction of the high-intensity laser pulse and the material generates new frequency components that can be of lower or higher frequency (greater or lower wavelength) compared to the pump wavelength and called Stokes and anti-Stokes, respectively. [3]

The effect described above transfers only a small fraction of power between two optical fields. A higher portion of energy ($\geq 10\%$) is transferred in simulated Raman scattering (SRS), when a seed pulse shifted in frequency corresponding to the maximum of the Raman gain co-propagate with the high-intensity pump laser. This process can also be self-seeded when the spectral bandwidth of a short pulse overlaps with that of the Raman gain, dynamics known as the self-frequency shift. [2, 3]

2.2 Fiber properties

An optical fiber consists of a core and a surrounding cladding with different refractive indices. The propagation of light in the fiber is based on total internal reflection at the core-cladding interface. Another parameter to control light propagation are optical modes. An optical mode defines the electromagnetic field pattern that is perpendicular to the propagation of the light rays in a waveguide. Each mode has an associated path for light propagation in an optical fiber.

The number of modes in a fiber can be determined with the V-parameter or fiber parameter,

$$V = 2\pi \frac{a}{\lambda_0} NA, \tag{2.5}$$

where a is the radius for the fiber core, λ_0 the wavelength of propagating light rays and NA is the numerical aperture [4]. The numerical aperture defines the acceptance angle for incoming light in order for total internal reflection to result.

Optical fibers can be divided in single-mode and multimode fibers, depending on the amount of modes they can support. As the name indicates, single-mode fibers (SMF) support only one mode and $V < 2.405$ [4]. Light has only one possible path along the optical axis to propagate because of the small core size of a single-mode fiber. Multimode fibers (MMF) have larger core sizes and thus increased numerical aperture compared to single-mode fibers, allowing more than one possible propagating path inside the fiber. For fibers with fiber parameter $V > 10$, the number of modes supported can be approximated as $M \approx \frac{V^2}{2}$ [2].

For an optical pulse to propagate in an optical fiber, refractive index value is important to take into consideration. Optical fibers can be differentiated into several different types based on their refractive index profiles. The most common refractive index profile types are step-index and graded-index (GRIN) profiles. Step-index refractive index profile has a constant-valued refractive index through the entire core of the fiber, and the refractive index on the cladding part is significantly smaller. This allows for total internal reflection to happen and light propagate inside the optical fiber.

GRIN refractive index profile has a down-opening parabola shape, and the highest refractive index is at the centre of the fiber core. Respectively, the lowest refractive index is detected on the core-cladding border. The refractive index profiles for step-index and graded-index fibers are shown on figure 2.1.

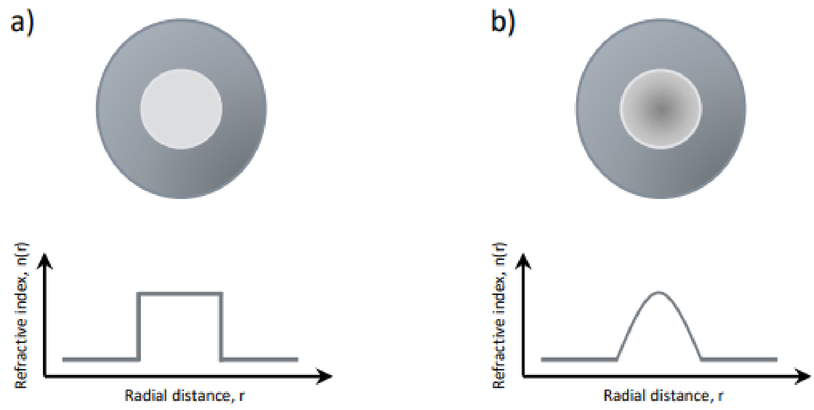


Figure 2.1. *Refractive index profiles for a) step-index fiber and b) graded-index fiber. [5]*

When light propagates in a step-index fiber, total internal reflection happens on the core-cladding border and light travelling in modes creates differences in group velocities. The refractive index profile of a GRIN fiber causes light rays to propagate in a sinusoidal form in a way that rays propagating closest to the axis travel at lowest phase velocity. Total internal reflection at the core-cladding border does not occur and refraction is caused by the refractive index profile. This causes GRIN fibers to have lower modal dispersion in comparison to step-index multimode fibers. In this thesis, we focus on the use of multimode step-index fibers on creating supercontinuum.

3. STATE OF THE ART

Supercontinuum generation based lasers and commercial devices are widely available in a broad variety of applications due to extensive research. Compared to a white light source, SC light sources are much brighter, with high spatial and even temporal coherence. For these reasons, they are often referred to as 'white-light' lasers.

3.1 Mid-infrared spectroscopy

The mid-infrared (MIR) region is the spectral region of 2.5 µm–25 µm [6]. This region that is also called molecular 'fingerprint region' contains the fundamental absorption signatures of most molecules and it is appropriate for a variety of applications. With MIR spectroscopy, non-intrusive analysis of a system can be executed and molecular structure of the matter investigated with high sensitivity. Analysis of detecting multiple molecules with absorption signatures relatively near to each other with the same device helps decrease the time needed for measurements and be cost-effective.

Certain properties are crucial for MIR SC light sources in order to be suitable for spectroscopic applications. Spectral brightness describes the spectral radiance of a light source and it is significant in determining the spectral power a system can transmit [6]. Another property to consider is beam quality of the laser source. A clean output beam has an effect on the spectral brightness as well as direct benefits on for example gas sensing applications.

Additionally, noise properties are important to consider for applications. Noise has an effect on long-term stability performance. When considering MIR SC light sources, spectral noise occurs because of nonlinear processes happen stochastically, meaning precise statical analysis of different phenomena are investigated but precise predictions are impossible to make. MIR SC light sources can have significant pulse-to-pulse fluctuations that can affect spectral broadening [7].

Several types of MIR light sources are on the market, but their availability is limited. Most common MIR spectrometers utilize thermal emitters that are based on emitting quasi-black-body radiation. Although the spectral coverage might be sufficient for most MIR spectroscopy applications, other limitations exist for their usage. Thermal emitters do not have good spatial coherence, and the optical power output level and thus brightness remains insufficient for some applications. [6] In order to use a MIR light source for applications, clean beam output is crucial. When using thermal emitters, the beam quality is not satisfactory.

Tunable laser diodes have been used for MIR spectroscopy for their high brightness and coverage of the needed spectrum. However, they have really low power levels and poor cooling capacities and thus have not spread for wider usage in spectroscopic applications. [6] Quantum cascade lasers solve many of the problems of the laser diodes by their compactibility, operating in room temperature and having sufficient average output power. Although quantum cascade lasers are available over the range from 3 µm to 15 µm, they typically only emit light at a single wavelength or have a very limited tuning range [8]. Optical parametric oscillators (OPO) are able to generate a broad array of wavelengths by using multiple optical components. This causes the device to be bulky and not suitable for all applications.

In order to overcome these limitations associated with a MIR light source, supercontinuum generation is taken into consideration. An all-fiber supercontinuum laser provides system that is compact and low-footprint, thus suitable for a wide variety of applications. Current interest is on cascading silica and soft-glass fibers and using a pump wavelength of 1550 nm to create SC extending to the MIR [9].

3.2 All-fiber supercontinuum source for mid-infrared

When creating an all-fiber MIR supercontinuum source, it is possible to achieve a broad wavelength coverage and high power levels while having a compact source. This source can be used for applications such as optical metrology, optical sensing and spectroscopy.

Current commercial supercontinuum fiber lasers are based on silica glass photonic crystal fibers (PCF) that have spectral coverage from 400 nm to 2400 nm [9]. PCF fibers have an unusual core-cladding structure, with a solid glass structure and air holes placed in a periodic lattice structure. This arrangement causes the refractive index difference with the core and the cladding to be greater than in traditional optical fibers. One of the benefits of a modifiable fiber structure is the ability to shift the ZDW of the fiber and open new possibilities for SC generation. [10]

The transmission window of silica-based optical fibers reaches 2.5 µm. In order to extend the spectrum into the MIR region, soft glass fibers need to be used. Extensive research has been made with step-index ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) for different spectroscopic applications in the MIR region. ZBLAN based broadband MIR SC light sources have been used to identify and measure concentration of acetylene and methane [11], to detect multiple gases simultaneously for quality control of fruit storaging [12] and to measure the diffuse reflection spectrum of paints and fertilizers remotely [13].

Soft glass fibers with higher nonlinearity and transparency window extending further into the MIR region compared to fluoride fibers have been researched. A cascade of silica, ZBLAN and chalcogenide (As_2Se_3) fibers were used to create SC from 2 µm to 10 µm to reach a significant part of the molecular fingerprint region with a compact fiber source. The output power was only 16 mW that can be too low for numerous applications. [14] A higher output power can be achieved using an optical fiber amplifier. SC from 1.6 µm to 11 µm with average output power of 139 mW was achieved with cascading silica, ZBLAN, arsenic sulfide (As_2S_3) and arsenic selenide (As_2Se_3) using thulium-doped amplifier stages [15]. With the use of an erbium/ytterbium fiber amplifier (EYFA), a cascade of silica and ZBLAN generated SC with bandwidth from 1 µm to 3.2 µm with average output power of 1.3 W [16].

Currently there are several supercontinuum white light laser sources commercially available that use fluoride-based fibers in order to broaden the spectrum. For example, Thorlabs, Inc. has a dispersion-engineered indium fluoride based MIR SC laser (SC4500) with wavelength range from 1300 nm to 4500 nm and output power of 110 mW over the MIR range from 2200 nm to 4200 nm [17]. Another commercially available supercontinuum laser is produced by Leukos (Electro MIR 4.8) with wavelength range from 800 nm to 4800 nm with average output power of 500 mW [18]. Similar other commercial devices are available as well, and the common factor for all of them is the use of single-mode fibers with creating supercontinuum. However, all the SC sources described above use single-mode fibers with a small core size and are thus limited in terms of power spectral density due to the low damage threshold. This thesis explores the possibilities of using step-index multimode fibers in order to increase the power output.

4. EXPERIMENTAL PART

4.1 Physical approach

The choice of optical fibers as the nonlinear generating medium is crucial for efficient supercontinuum generation. The transmission window of an optical fiber needs to be as broad as possible in order to generate an extensive SC in addition of having high nonlinearity. Using silica glass (silicon dioxide, SiO_2) as part of the SC is common due to great optical and mechanical properties of the material. SC broadening to the MIR region with pure silica is not possible to achieve due to the strong material absorption at 2.5 µm, and fibers with a longer transparency window into the MIR region are required [19].

Soft glass fibers such as fluoride-based fluorozirconate or ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) and indium(III)fluoride (InF_3) fibers have higher nonlinearity and broader transparency window to the MIR when compared to silica. The transmission window for the aforementioned fluoride fibers span to the MIR spectral region, for ZBLAN from 0.29 µm to 4.5 µm and InF_3 from 0.31 µm to 5.5 µm, respectively.

When creating a mid-infrared supercontinuum source, other thing to consider is dispersion and the nonlinear effects that arise from it. Depending on the pump wavelength and the fiber material used, the regime of dispersion affects the generated SC dramatically. The zero dispersion wavelength for silica based optical fibers is approximately 1.30 µm and for fluoride based fibers, the ZDW is approximately 1.6 µm–1.8 µm. When using a pump wavelength at 1.55 µm, the dispersion regimes are different for the cascaded fibers. Because the broadest spectra is generated at the anomalous dispersion regime close to the ZDW of the optical fiber, the initial supercontinuum is generated using the silica with a higher damage threshold and anomalous dispersion regime, and then extended into the mid-infrared using a soft-glass fiber with ZDW in the normal dispersion regime.

4.2 Experimental realization

This section introduces the experiments done for creating SC in an all-fiber setup. The experiments were done in the Ultrafast Photonics research group at Tampere University.

4.2.1 Setup

The experimental laboratory setup is shown in figure 4.1. Laser pulses are generated using a fiber laser (Keopsys Lumibird PEFL-M01) with a center wavelength of 1545 nm, pulse duration of 0.5 ns and repetition rate of 250 kHz. The laser has a fibered output with core size of 20 µm.

The fiber output of the laser is connected directly to the optical fiber using a mating sleeve. This allows for two optical fibers to have appropriate alignment and reduce the amount of loss when coupling light straight to another fiber. All fibers used in the cascade are connected with mating sleeves.

After the final fiber in the cascade, supercontinuum light is guided through a reflective collimator (RC) to collimate the light using a metallic mirror. The collimated light is then directed through a biconvex lens and a multimode fiber in order to cut down the power for the analyzing device. The generated SC was measured using an optical spectrum analyzer (OSA), and two separate devices were used with spectral ranges of 350-1700 nm and 1500-3400 nm, respectively.

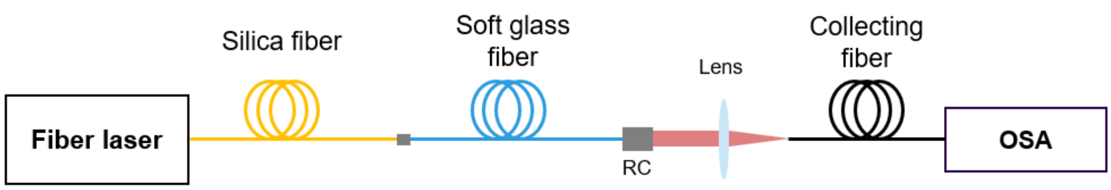


Figure 4.1. *Experimental setup for the SC generation measurements.*

4.3 Results

Measurements with the setup described earlier were executed using different combinations of multimode step-index silica and single-mode or multimode soft glass fibers. In order to see the effects of broadening and power limitations, SC was measured using varying input powers.

4.3.1 SCG with multimode step-index silica fibers

First measurements were done with a multimode step-index silica fiber with a core size of 25 µm and length of 2 m. The fiber has a numerical aperture (NA) of 0.1. The generated supercontinuum with fiber mentioned above at input powers of 1427 mW, 2020 mW and 2560 mW can be seen as function of the pump wavelength in figure 4.2.

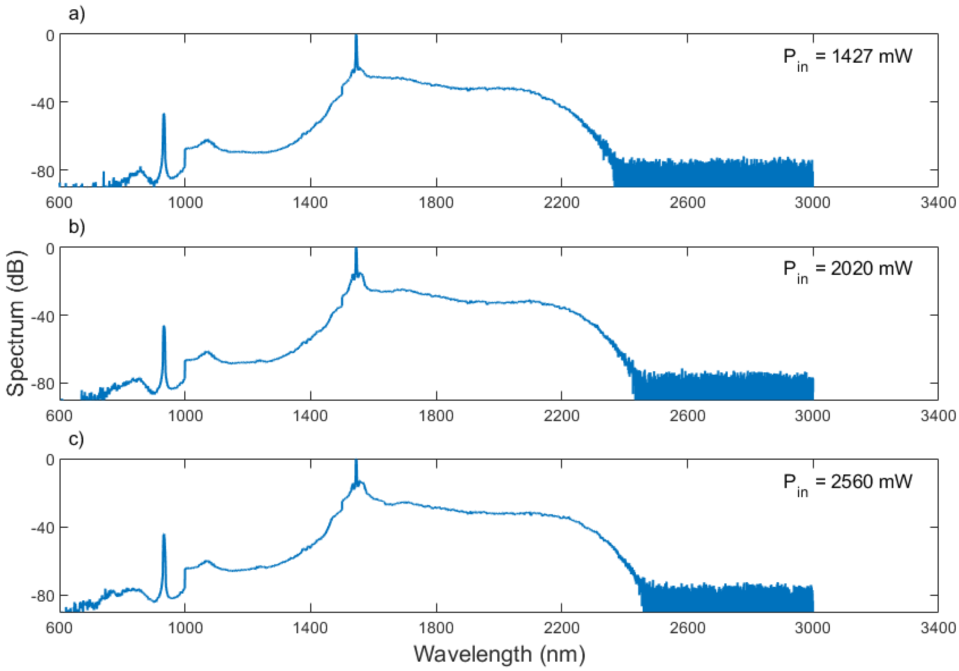
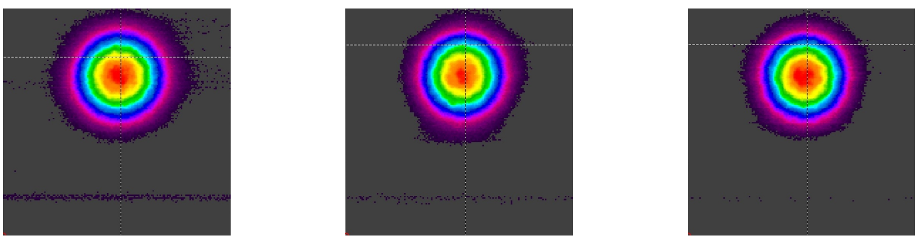


Figure 4.2. *Generated supercontinuum spectra for step-index silica fiber as a function of power.*

When the input power increases, spectral broadening widens and the broadest spectrum generated spans from 730 nm to 2450 nm as seen in figure 4.2 c) with input power of 2560 mW. The output power at the output of the silica fiber and after the reflective collimator is calculated to be $\approx$ 75 % of the input power for each measurement. The importance of a clean beam profile for applications was discussed in chapter 3. Beam profile images were taken to ensure a clean output beam using different narrowband filters. Beam profiles for step-index silica with 25 µm core size are shown in figure 4.3. As seen in the figure, beam profiles are clean and with circular symmetry.



(a) 1640 nm ***(b)*** 1710 nm ***(c)*** 1810 nm

Figure 4.3. *Far-field images of output beam profile at different wavelengths of the SC spectrum for multimode step-index silica fiber with $P_{in} = 1755$ mW.*

The bandwidth of silica reaches 2600 nm and reaching MIR wavelengths is not possible even with increasing input power. Soft-glass fibers are needed to extend the spectrum and one example is ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF).

Measurements were made with cascading the previously discussed step-index silica with core of 25 µm and length of 2 m to a step-index single-mode ZBLAN with core of 9 µm and length of 5 m. Spectra with two input powers are shown on figure 4.4. As seen from the results, spectral broadening with cascaded silica and ZBLAN reaches the MIR region. With input power of 2020 mW the bandwidth of the generated supercontinuum is from 750 nm to 3350 nm and reduced for lower input powers.

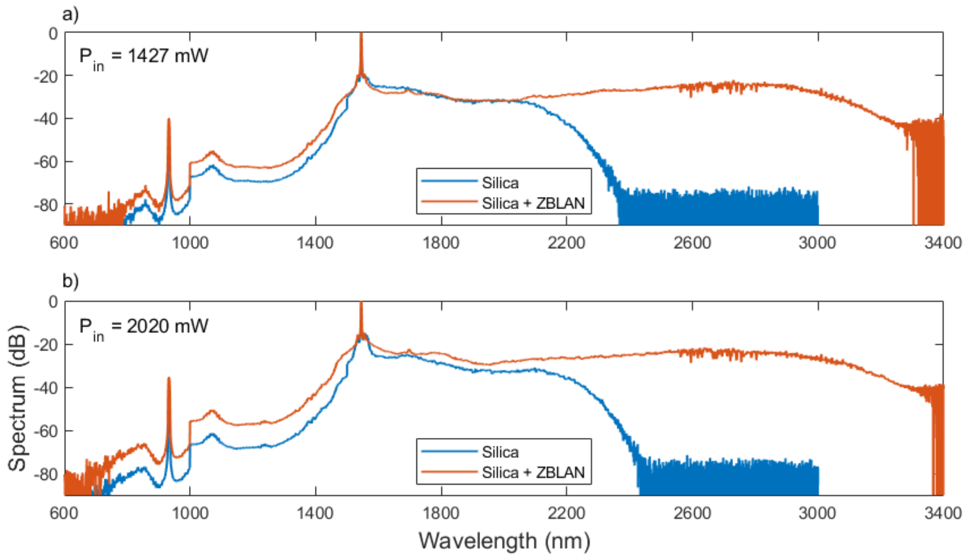


Figure 4.4. *Generated supercontinuum spectra for cascade of step-index silica fiber and single-mode ZBLAN as a function of power.*

The calculated coupling efficiency as the ratio of output average power with input average power was only ≈ 17 % for these measurements. This is because of the difference in the core sizes of the silica and ZBLAN causes power loss. Since the ZBLAN is a single-mode fiber, it only has one possible mode and the beam profile is clean and with circular symmetry.

In order to test different combinations of silica and soft glass fibers to optimize broadening as well as coupling efficiency, measurements were made using the aforementioned step-index silica cascaded with an (InF_3) multimode fiber with core of 30 µm and length of 2 m. Results are shown on figure 4.5.

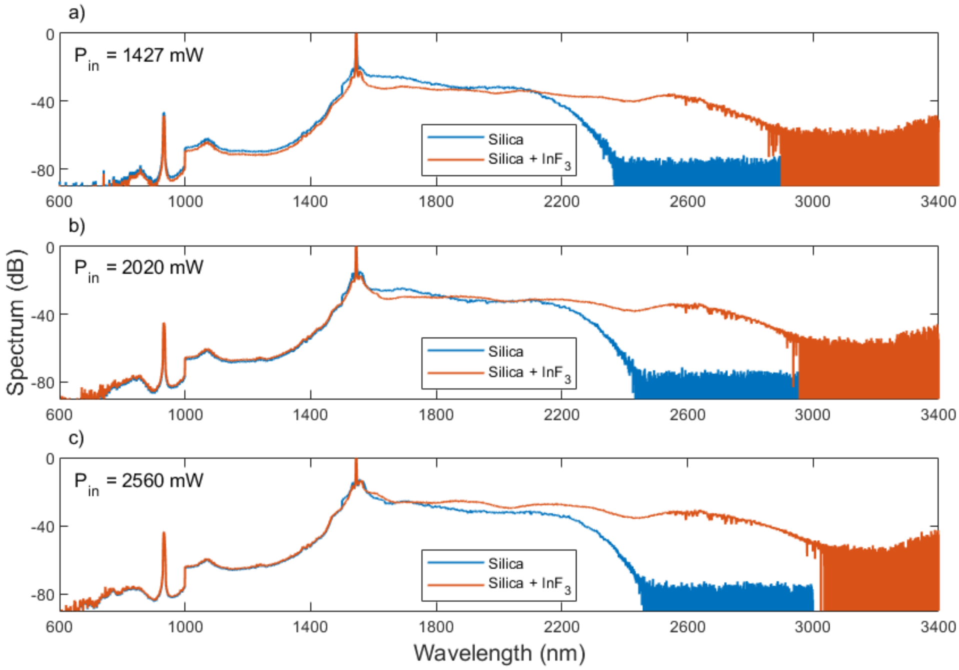
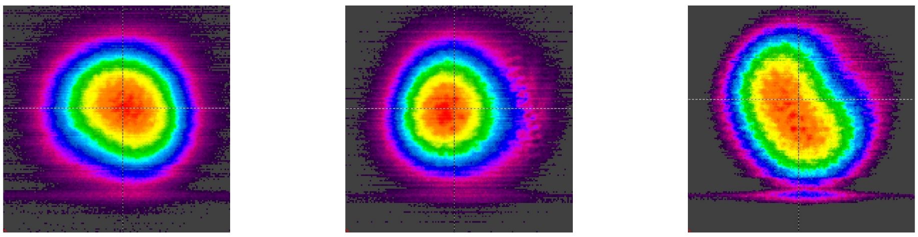


Figure 4.5. *Generated supercontinuum spectra for cascade of step-index silica fiber and InF_3 as a function of power.*

In comparison to the cascade with ZBLAN, the bandwidth is not as broad, although reaching from 730 nm to 3000 nm with input power of 2560 mW. On the contrary, the coupling efficiency was calculated at $\approx$ 70 %, with over 1700 mW with input power mentioned above. Because the used fluoride fiber is now a multimode fiber, beam profiles were measured and shown in figure 4.6.



(a) 1640 nm ***(b)*** 1710 nm ***(c)*** 1810 nm

Figure 4.6. *Far-field images of output beam profile at different wavelengths of the SC spectrum for multimode step-index silica and indium(III)fluoride with* $P_{in} = 1760\,\text{mW}$.

As seen from the beam profiles, they are not completely round with their circular symmetry. On the other hand, the beam profiles are not speckled which indicates them not being clean and thus unusable for applications in for example spectroscopy. With the wavelength of the narrowband filter closer to the wavelength of the pump, the intensity distribution is more circular than moving further away.

5. CONCLUSION

This thesis discussed current state-of-the-art supercontinuum generation based spectroscopic applications in the mid-infrared region. Recently creating an all-fiber supercontinuum source that has spectral broadening in the MIR region has sparked interest.

Current SC sources are based on using single-mode soft glass fibers with a low damage threshold and limited power spectral density. For increased damage threshold, the usage of multimode fibers is considered for SC applications in the mid-infrared. A higher output power is crucial for applications in spectroscopy and remote sensing that require a broadband light source.

In this work, we have tested the possibility to generate supercontinuum spanning in the mid-infrared spectral region using a cascade of multimode step-index silica fiber and single-mode and multimode fluoride fiber. We were able to achieve spectral broadening from 730 nm to 3000 nm with $\approx$ 70 % power output which is more than in currently available commercial supercontinuum based 'white-light' lasers in the mid-infrared. Due to the fact of a larger core size and smaller nonlinearity, the spectrum does not extend as far as supercontinuum generated with using single-mode fibers. There can still be improvements made for the spectral bandwidth extending further in the mid-infrared.

In the future, it will be interesting to form similar experiments with cascading a multimode silica with a soft glass fiber except using graded-index silica fibers instead of step-index. Fibers with a graded-index refractive index profile are known to preserve excellent beam quality due to specific spatiotemporal nonlinear dynamics and construct an interesting opportunity for SC in the MIR region.

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