SYSTEM FOR GENERATING MID-INFRARED LIGHT AND METHOD OF FORMING THE SAME

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority of Singapore application No. 10202401106Q filed April 16, 2024 and Singapore application No. 10202401134Q filed April 18, 2024, the contents of them being hereby incorporated by reference in their entirety for all purposes.

TECHNICAL FIELD

[0002] Various embodiments of this disclosure may relate to a system for generating a mid-infrared (MIR) light. Various embodiments of this disclosure may relate to a method of forming a system for generating a mid-infrared (MIR) light.

BACKGROUND

[0003] Ultrafast mid-infrared (MIR) light sources generating high-energy pulses have a long list of applications across many disciplines, including molecular spectroscopy, precision manufacturing, extreme nonlinear optics, attosecond science, and organic sample processing. The techniques employed in most of these systems rely on parametric processes in nonlinear crystals, which have the major drawback of requiring careful beam alignment. As such, these sources are often vulnerable to external vibrations, limiting their operations exclusively to well-controlled laboratory environments.

[0004] Fiber-based systems can eliminate this shortfall and offer robustness and versatility outside laboratories. However, conventional silica optical fibers cannot be used as they do not transmit in MIR. Optical fibers, made from compound-glass materials, such as fluoride, tellurite, and chalcogenide, have been quite effective in this respect. However, these fibers are not suitable for high-power applications due to their poor material stability at high temperatures.

[0005] Antiresonant hollow-core fibers (AR-HCFs) that guide light in the central hollow region have emerged as a promising fiber platform for MIR light sources. Their low-loss MIR

guidance and ability to stage efficient light-matter interactions through gas filling make them ideal for mediating nonlinear frequency conversion to generate MIR pulses.

[0006] In this regard, generation of microjoule-level femtosecond pulses in the 3–4 μm range has previously been reported. The unique dispersion landscape near the red edge of a transmission band in AR-HCF enabled the phase-matched conversion of the near-infrared pump to MIR through dispersive wave generation. However, efforts to enhance the conversion efficiency of energy into MIR of longer wavelengths have reached a plateau, imposing an inherent constraint on the maximum achievable pulse energy as well as maximum emission wavelength solely through this method. Additionally, the central wavelength of the resulting MIR signal is predominantly dictated by the tube wall thickness, posing a challenge to achieving tunability in the source.

SUMMARY

[0007] Various embodiments may relate to a system for generating mid-infrared light. The system may include a first laser source configured to provide an infrared light having a wavelength selected from a range from 1 μm to 2.5 μm. The system may also include a second laser source configured to provide a further light having a wavelength shorter than the wavelength of the infrared light provided by the first laser source. The system may additionally include an optical element configured to combine the infrared light provided by the first laser source and the further light provided by the second laser source into a combined light. The system may also include a first gas cell configured to hold a gas, and a second gas cell configured to hold the gas. The system may additionally include a hollow core fiber (HCF) in fluidic communication with the first gas cell and the second gas cell such that the hollow core fiber is also configured to hold the gas. The hollow core fiber when filled with the gas may be configured to emit the mid-infrared (MIR) light in response to the combined light being provided to the hollow core fiber, the mid-infrared (MIR) light having a wavelength in a mid-infrared range.

[0008] In various other embodiments, the first laser source may be configured to self-spectrally broadened to provide the further light by itself, eliminating the need for the second laser source. In other words, the system may include a first laser source configured to provide an infrared light having a wavelength selected from a range from 1 μm to 2.5 μm. The system may not have or require a beam combiner. The system may also include a first gas cell

configured to hold a gas, and a second gas cell configured to hold the gas. The system may additionally include a hollow core fiber (HCF) in fluidic communication with the first gas cell and the second gas cell such that the hollow core fiber is also configured to hold the gas. The hollow core fiber when filled with the gas may be configured to emit the mid-infrared (MIR) light in response to the infrared light being provided to the hollow core fiber, due to self-spectral broadening of the infrared light to provide or generate a further light having a wavelength shorter than the wavelength of the infrared light provided by the first laser source. The further light and the infrared light may then interact with each other to generate the MIR light. The mid-infrared (MIR) light may have a wavelength in a mid-infrared range. The wavelength of the MIR light may be tuned by varying a pressure of the gas.

[0009] Various embodiments may relate to a method of forming a system for generating a mid-infrared (MIR) light. The method may include providing a first laser source configured to provide an infrared light having a wavelength selected from a range from 1 μm to 2.5 μm. The method may also include providing a second laser source configured to provide a further light having a wavelength shorter than the wavelength of the infrared light provided by the first laser source. The method may further include providing an optical element configured to combine the infrared light provided by the first laser source and the further light provided by the second laser source into a combined light. The method may additionally include providing a first gas cell configured to hold a gas. The method may also include providing a second gas cell configured to hold the gas. The method may further include arranging or coupling a hollow core fiber (HCF) to be in fluidic communication with the first gas cell and the second gas cell such that the hollow core fiber is also configured to hold the gas. The hollow core fiber when filled with the gas may be configured to emit the mid-infrared (MIR) light in response to the combined light being provided to the hollow core fiber, the mid-infrared (MIR) light having a wavelength in a mid-infrared range.

[0010] In various other embodiments, the first laser source may be configured to self-spectrally broadened to provide the further light by itself, eliminating the need for the second laser source. In other words, the method may include providing a first laser source configured provide an infrared light having a wavelength selected from a range from 1 μm to 2.5 μm. The system may not have or require a beam combiner. The method may also include providing a first gas cell configured to hold a gas. The method may further include providing a second gas cell configured to hold the gas. The method may further include arranging or coupling a hollow

core fiber (HCF) to be in fluidic communication with the first gas cell and the second gas cell such that the hollow core fiber is also configured to hold the gas. The hollow core fiber when filled with the gas may be configured to emit the mid-infrared (MIR) light in response to the infrared light being provided to the hollow core fiber, due to self-spectral broadening of the infrared light to provide or generate a further light having a wavelength shorter than the wavelength of the infrared light provided by the first laser source. The further light and the infrared light may then interact with each other to generate the mid-infrared (MIR) light. The mid-infrared (MIR) light may have a wavelength in a mid-infrared range.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily drawn to scale, emphasis instead generally being placed upon illustrating the principles of various embodiments. In the following description, various embodiments of the invention are described with reference to the following drawings.

FIG. 1 shows a general illustration of a system for generating a mid-infrared (MIR) light according to various embodiments.

FIG. 2 shows a general illustration of a method of forming a system for generating a mid-infrared (MIR) light according to various embodiments.

FIG. 3 shows (a) a schematic of a system for generating a mid-infrared (MIR) light; and (b) a scanning electron micrograph of a cross-section of an antiresonant hollow-core fiber (AR-HCF) according to various embodiments.

FIG. 4A shows (a) a plot of input spectral intensity (in arbitrary units or a.u.) / output spectral intensity (in arbitrary units or a.u.) as a function of wavelength (in micrometers or μm) illustrating the output spectrum of the mid-infrared (MIR) light (solid line) generated by the system under pressure of 20 bar argon with pump laser (dotted line) having energy of 50 μJ and seed laser (dashed line) having energy of 1 μJ according to various embodiments; and (b) a plot of phase mismatch $\Delta\beta$ (in per centimeter or /cm) as a function of wavelength (in micrometers or μm) illustrating the corresponding degenerate four-wave mixing (DFWM) phase matching diagram according to various embodiments.

FIG. 4B shows a plot of input spectral intensity (in arbitrary units or a.u.) / output spectral intensity (in arbitrary units or a.u.) as a function of wavelength (in micrometers or μm) illustrating (i) the output spectrum of the mid-infrared (MIR) light generated by the system under pressure of 20 bar argon with pump laser having energy of 50 μJ and seed laser having energy of 1 μJ according to various embodiments; and (ii) the output spectrum of the mid-infrared (MIR) light generated by the system without the seed laser according to various embodiments.

FIG. 5 illustrates characterization of the mid-infrared pulses at 3 μm - 4 μm range: (a) a plot of intensity (in arbitrary units or a.u.)/chirp (in radians per pico-seconds or rad/ps) as a function of delay (in femto-seconds or fs) illustrating the intensity (solid line) and phase (dotted line) profiles of the mid-infrared pulses according to various embodiments; (b) a plot of spectrum (in arbitrary units or a.u.) as a function of wavelength (in micro-meters or μm) illustrating the measured spectrum (solid line) and reconstructed spectrum (dashed line) according to various embodiments; and (c) plots of wavelength (in micrometers or μm) as a function of delay (in femtoseconds or fs) showing acquired (left) and reconstructed (right) spectrograms according to various embodiments.

FIG. 6 shows (a) a plot of intensity (in arbitrary units or a.u.) as a function of wavelength (in micro-meters or μm) illustrating the output spectrum of the mid-infrared (MIR) light generated by the system under pressure of 11 bar (solid line), 17 bar (dashed line) and 23 bar (dotted line) according to various embodiments; and (b) a plot of phase mismatch $\Delta\beta$ (in per centimeter or /cm) as a function of wavelength (in micrometers or μm) illustrating the corresponding degenerate four-wave mixing (DFWM) phase matching diagram according to various embodiments.

DESCRIPTION

[0012] The following detailed description refers to the accompanying drawings that show, by way of illustration, specific details and embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and structural, logical, and electrical changes may be made without departing from the scope of the invention. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

[0013] Features that are described in the context of an embodiment may correspondingly be applicable to the same or similar features in the other embodiments. Features that are described in the context of an embodiment may correspondingly be applicable to the other embodiments, even if not explicitly described in these other embodiments. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of an embodiment may correspondingly be applicable to the same or similar feature in the other embodiments.

[0014] In the context of various embodiments, the articles "a", "an" and "the" as used with regard to a feature or element include a reference to one or more of the features or elements.

[0015] In the context of various embodiments, the term "about" or "approximately" as applied to a numeric value encompasses the exact value and a reasonable variance, e.g., within 10% of the specified value.

[0016] As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

[0017] By "comprising" it is meant including, but not limited to, whatever follows the word "comprising". Thus, use of the term "comprising" indicates that the listed elements are required or mandatory, but that other elements are optional and may or may not be present.

[0018] By "consisting of" it is meant including, and limited to, whatever follows the phrase "consisting of". Thus, the phrase "consisting of" indicates that the listed elements are required or mandatory, and that no other elements may be present.

[0019] Embodiments described in the context of one of the systems are analogously valid for the other systems. Similarly, embodiments described in the context of a method are analogously valid for a system, and vice versa.

[0020] Various embodiments may overcome the abovementioned limitations to generate high-energy MIR pulses with substantially better conversion efficiencies and more flexibility on wavelength tunability. Various embodiments may relate to the injection of a low-intensity seed at a specific wavelength in near-infrared (NIR) to stimulate degenerate four-wave mixing (DFWM) and produce high-energy pulses with high tunability in the AR-HCF. The generated MIR wavelength may be extensively tuned across the range of 2.5 μm to 6 μm or even 10 μm by modifying both the fiber structure and seed laser. Various embodiments may relate to a system including any HCF capable of containing gas to provide sufficient nonlinearity and dispersion, including but not restricted to an AR-HCF.

[0021] FIG. 1 shows a general illustration of a system for generating a mid-infrared (MIR) light according to various embodiments. The system may include a first laser source 102 configured to provide an infrared light having a wavelength selected from a range from 1 μm to 2.5 μm. The system may also include a second laser source 104 configured to provide a further light having a wavelength shorter than the wavelength of the infrared light provided by the first laser source 102. The system may additionally include an optical element 106 configured to combine the infrared light provided by the first laser source 102 and the further light provided by the second laser source 104 into a combined light. The system may also include a first gas cell 108 configured to hold a gas, and a second gas cell 110 configured to hold the gas. The system may additionally include a hollow core fiber (HCF) 112 in fluidic communication with the first gas cell 108 and the second gas cell 110 such that the hollow core fiber 112 is also configured to hold the gas. The hollow core fiber 112 when filled with the gas may be configured to emit the mid-infrared (MIR) light in response to the combined light being provided to the hollow core fiber 112, the mid-infrared (MIR) light having a wavelength in a mid-infrared range.

[0022] In other words, the system may include a first laser source 102 for generating an infrared light, a second laser source 104 for generating a further light with a wavelength shorter than that of the infrared light, as well as an optical element 106 to combine the infrared light and the further light. The combined light including the infrared light and the further light may then be provided to a gas-filled hollow core fiber 112 fluidically coupled to a first gas cell 108 and a second gas cell 110 to generate a mid-infrared (MIR) light.

[0023] For avoidance of doubt, FIG. 1 seeks to illustrate features of a system for generating MIR according to various embodiments, and is not intended to limit, for instance, the shape, size, orientation, arrangement etc. of the various features.

[0024] The infrared light having the wavelength selected from a range from 1 μm to 2.5 μm may be a pump beam (alternatively referred to as "pump" or "pump laser"). The pump beam may be of sub-100 fs duration. The pump beam may provide pump photons.

[0025] The further light may be a seed beam. In various embodiments, the further light may be a near infrared (NIR) light. The NIR light may be a NIR seed beam (alternatively referred to as "NIR seed" or "seed laser"). The NIR light may provide signal photons.

[0026] In various embodiments, the mid-infrared (MIR) light may include mid-infrared (MIR) pulses. The MIR light may be referred to as "output". In this regard, an "output spectrum" may refer to a spectrum of the MIR light. The MIR light may include idler photons.

[0027] In various embodiments, the wavelength of the mid-infrared (MIR) light may be inversely proportional to the wavelength of the further light. As the wavelength of the further light increases, the wavelength of the MIR light may decrease. Conversely, as the wavelength of the further light decreases, the wavelength of the MIR light may increase.

[0028] In various embodiments, the wavelength of the mid-infrared (MIR) light may be of a value selected from a range from 2.5 μm to 10 μm.

[0029] In various embodiments, the wavelength of the mid-infrared (MIR) light may be of a value selected from a range from 3 μm to 4 μm. In various embodiments, the wavelength of the MIR light that can be generated may have a value beyond 4 μm, e.g., 4.57 μm.

[0030] In various embodiments, the wavelength of the further light may be of a value selected from a range from 0.6 μm to 1.7 μm.

[0031] In various embodiments, the wavelength of the mid-infrared (MIR) light may be directly proportional to a gas pressure of the gas in the hollow core fiber 112. As the gas pressure increases, the wavelength of the MIR light may increase. Conversely, as the gas pressure decreases, the wavelength of the MIR light may decrease. For avoidance of doubt, the phrase "filled with gas" may refer to the hollow core fiber 112 having any suitable pressure and/or density of gas. In various embodiments, the gas may be any suitable gas, for instance argon (Ar), helium (He) or xenon (Xe).

[0032] In various embodiments, the hollow core fiber 112 may include a cladding defining a hollow core. The hollow core may be provided with gas during operation of the system. The diameter of the hollow core may be selected from a range from 60 μm to 140 μm. The optimum value of the core diameter may depend on the desired wavelength of the generated MIR pulses.

[0033] The hollow core fiber 112 may be any suitable type or kind of hollow core fiber. In various embodiments, the hollow core fiber 112 may be an antiresonant hollow core fiber (AR-HCF). The antiresonant hollow core fiber (AR-HCF) may achieve higher efficiency.

[0034] In various embodiments, a diameter of a core of the hollow core fiber 112 may be of a value selected from a range from 60 μm to 140 μm. In various embodiments, a thickness of a cladding of the hollow core fiber 112 may be of a value selected from 1.2 μm to 3.2 μm.

[0035] In various embodiments, the mid-infrared (MIR) light may be generated via degenerate four-wave-mixing (DFWM).

[0036] In various embodiments, the optical element 106 (i.e., for combining the infrared light provided by the first laser source and the further light provided by the second laser source) may be any suitable element that can combine the infrared light and the further light, for instance, a dichroic mirror, a wavelength-division multiplexer, a dispersion grating, or a cube beam splitter.

[0037] In various embodiments, the system may include a delay line arranged either along a first optical path or along a second optical path. The first optical path may refer to a transmission path taken by the infrared light from the first laser source 102 to the optical element 106, while the second optical path may refer to a transmission path taken by the further light from the second laser source 104 to the optical element 106. The delay line may control or provide a temporal overlap of the infrared light and the further light in the gas-filled hollow core fiber 112.

[0038] In various embodiments, the system may include a first set of (additional) optical elements arranged along the first optical path for controlling an input energy of the infrared light provided by the first laser source 102. The system may also include a second set of (additional) optical elements arranged along the second optical path for controlling an input energy of the further light provided by the second laser source 104.

[0039] In various embodiments, the first set of (additional) optical elements may include a half-wave plate and a polarizer. The second set of (additional) optical elements may also include a half-wave plate and a polarizer.

[0040] In various embodiments, the system may also include a mirror along the second optical path, the mirror configured to direct the further light towards the optical element 106 (i.e., the optical element for combining the infrared light provided by the first laser source 102 and the further light provided by the second laser source 104).

[0041] In various embodiments, the system may additionally include a focus or collimate lens configured to focus the combined light onto within the hollow core fiber 112 or collimate the combined light for transmission. The focus lens may be configured to focus the combined light to within the hollow core fiber 112, while the collimate lens may be configured to collimate the combined light for transmission.

[0042] In various other embodiments, the system may include a first laser source 102 configured provide an infrared light having a wavelength selected from a range from 1 μm to 2.5 μm. The system may not have or require a second laser source 104 or a beam combiner 106. The system may also include a first gas cell 108 configured to hold a gas, and a second gas cell 110 configured to hold the gas. The system may additionally include a hollow core fiber (HCF) 112 in fluidic communication with the first gas cell and the second gas cell such that the hollow core fiber 112 is also configured to hold the gas. The hollow core fiber 112 when filled with the gas may be configured to emit the mid-infrared (MIR) light in response to the infrared light being provided to the hollow core fiber 112, due to self-spectral broadening of the infrared light to provide or generate a further light having a wavelength shorter than the wavelength of the infrared light provided by the first laser source 102. The further light and the infrared light may then interact with each other to generate the mid-infrared (MIR) light. The mid-infrared (MIR) light may have a wavelength in a mid-infrared range. The mid-infrared (MIR) light may be generated due to degenerate four-wave-mixing (DFWM). Self-spectral broadening may occur due to nonlinear effects. The generation of the MIR light using a single laser source and via self-spectral broadening may be less efficient compared to generation of the MIR light using two laser sources.

[0043] FIG. 2 shows a general illustration of a method of forming a system for generating a mid-infrared (MIR) light according to various embodiments. The method may include, in 202, providing a first laser source configured to provide an infrared light having a wavelength selected from a range from 1 μm to 2.5 μm. The method may also include, in 204, providing a second laser source configured to provide a further light having a wavelength shorter than the wavelength of the infrared light provided by the first laser source. The method may further include, in 206, providing an optical element configured to combine the infrared light provided by the first laser source and the further light provided by the second laser source into a combined light. The method may additionally include, in 208, providing a first gas cell configured to hold a gas. The method may also include, in 210, providing a second gas cell configured to hold the gas. The method may further include, in 212, arranging or coupling a hollow core fiber (HCF) to be in fluidic communication with the first gas cell and the second gas cell such that the hollow core fiber is also configured to hold the gas. The hollow core fiber when filled with the gas may be configured to emit the mid-infrared (MIR) light in response to

the combined light being provided to the hollow core fiber, the mid-infrared (MIR) light having a wavelength in a mid-infrared range.

[0044] In other words, various embodiments may relate to a method to form a system for generating a mid-infrared (MIR) light. A hollow core fiber may be arranged or coupled to be in fluidic communication with a first gas cell and a second gas cell. A first laser source, a second laser source, and an optical element may be provided or arranged such that an infrared light generated by the first laser source and a further light generated by the second laser source may be combined by the optical element into a combined light, before the combined light is provided to the hollow core fiber with gas.

[0045] For avoidance of doubt, FIG. 2 is intended to illustrate steps of a method according to various embodiments, and is not intended to limit the sequence of the various steps. For instance, step 208 may occur before, after or at the same time as step 210.

[0046] In various embodiments, the mid-infrared (MIR) light may include mid-infrared (MIR) pulses.

[0047] In various embodiments, the wavelength of the mid-infrared (MIR) light may be inversely proportional to the wavelength of the further light.

[0048] In various embodiments, the wavelength of the mid-infrared (MIR) light may be of a value selected from a range from 2.5 μm to 10 μm.

[0049] In various embodiments, the wavelength of the mid-infrared (MIR) light may be of a value selected from a range from 3 μm to 4 μm. In various embodiments, the wavelength of the MIR light that can be generated may have a value beyond 4 μm, e.g., 4.57 μm.

[0050] In various embodiments, the wavelength of the further light may be of a value selected from a range from 0.6 μm to 1.7 μm.

[0051] In various embodiments, the further light may be a near infrared (NIR) light.

[0052] In various embodiments, the wavelength of the mid-infrared (MIR) light may be directly proportional to a gas pressure of the gas in the hollow core fiber.

[0053] In various embodiments, the hollow core fiber may be an antiresonant hollow core fiber (AR-HCF).

[0054] In various embodiments, a diameter of a core of the hollow core fiber may be of a value selected from a range from 60 μm to 140 μm. In various embodiments, a thickness of a cladding of the hollow core fiber may be of a value selected from 1.2 μm to 3.2 μm.

[0055] In various embodiments, the mid-infrared (MIR) light may be generated via degenerate four-wave-mixing (DFWM).

[0056] In various embodiments, the optical element (i.e., for combining the infrared light provided by the first laser source and the further light provided by the second laser source) may be any suitable element that can combine the infrared light and the further light, for instance, a dichroic mirror, a wavelength-division multiplexer, a dispersion grating, or a cube beam splitter.

[0057] In various embodiments, the method may include arranging a delay line either along a first optical path or along a second optical path.

[0058] In various embodiments, the method may also include arranging a first set of (additional) optical elements along the first optical path for controlling an input energy of the infrared light provided by the first laser source. The method may further include arranging a second set of (additional) optical elements along the second optical path for controlling an input energy of the further light provided by the second laser source.

[0059] In various embodiments, the first set of (additional) optical elements may include a half-wave plate and a polarizer. The second set of (additional) optical elements may include a half-wave plate and a polarizer.

[0060] In various embodiments, the method may also include providing a mirror along the second optical path, the mirror configured to direct the further light towards the optical element (i.e., the optical element for combining the infrared light provided by the first laser source and the further light provided by the second laser source).

[0061] In various embodiments, the method may further include providing a focus or collimate lens configured to focus the combined light onto within the hollow core fiber or collimate the combined light for transmission.

[0062] In various other embodiments, the method may include, in 202, providing a first laser source configured provide an infrared light having a wavelength selected from a range from 1 μm to 2.5 μm. Steps 204 and 206 may not be required. The method may also include, in 208, providing a first gas cell configured to hold a gas. The method may further include, in 210, providing a second gas cell configured to hold the gas. The method may further include, in 212, arranging or coupling a hollow core fiber (HCF) to be in fluidic communication with the first gas cell and the second gas cell such that the hollow core fiber is also configured to hold the gas. The hollow core fiber when filled with the gas may be configured to emit the

mid-infrared (MIR) light in response to the infrared light being provided to the hollow core fiber, due to self-spectral broadening of the infrared light to provide or generate a further light having a wavelength shorter than the wavelength of the infrared light provided by the first laser source. The further light and the infrared light may then interact with each other to generate the mid-infrared (MIR) light. The mid-infrared (MIR) light may have a wavelength in a mid-infrared range.

[0063] Various embodiments may relate to a method of operating a system for generating a mid-infrared (MIR) light. The method may include filling or providing a hollow core fiber (HCF) with a gas, the hollow core fiber in fluidic communication with the first gas cell (configured to hold the gas) and the second gas cell (also configured to hold the gas). The method may also include providing an infrared light having a wavelength selected from a range from 1 μm to 2.5 μm (using a first laser source). The method may further include providing a further light (using a second laser source), the further light having a wavelength shorter than the wavelength of the infrared light provided by the first laser source. The infrared light and the further light may be combined into a combined light provided to the hollow core fiber filled with gas. The hollow core fiber when filled or provided with the gas may be configured to emit the mid-infrared (MIR) light in response to the combined light being provided to the hollow core fiber, the mid-infrared (MIR) light having a wavelength in a mid-infrared range.

[0064] In various other embodiments, the further light may be removed if the pump (i.e., infrared light) can generate the required further light by itself. The method may include filling or providing a hollow core fiber (HCF) with a gas, the hollow core fiber in fluidic communication with the first gas cell (configured to hold the gas) and the second gas cell (also configured to hold the gas). The method may also include providing an infrared light having a wavelength selected from a range from 1 μm to 2.5 μm (using a first laser source) to the hollow core fiber filled with gas. The hollow core fiber when filled with the gas may be configured to emit the mid-infrared (MIR) light in response to the infrared light being provided to the hollow core fiber, due to self-spectral broadening of the infrared light to provide or generate a further light having a wavelength shorter than the wavelength of the infrared light provided by the first laser source. The further light and the infrared light may then interact with each other to generate the mid-infrared (MIR) light. The mid-infrared (MIR) light may have a wavelength in a mid-infrared range.

[0065] Various embodiments may relate to a method for generating high-power MIR pulses within a gas-filled HCF. Various embodiments may relate to pumping the fiber with a high-power near-infrared femtosecond laser and seeding it with a low-intensity laser at a shorter wavelength. The low-intensity laser may be removed if the first laser source can generate the required seed light by itself, i.e., via self-spectral broadening of the high-power near-infrared femtosecond laser. Notably, the inclusion of the shorter-wavelength seed may facilitate efficient energy transfer from the outset, leading to enhanced conversion efficiency. Moreover, various embodiments may enable tunability of the central wavelength of the MIR pulse by adjusting the pressure within the system.

[0066] Various embodiments may generate high-energy MIR pulses efficiently, requiring only a small seed to initiate energy transfer from the outset. Moreover, the central wavelength of the resulting MIR output may be precisely controlled by adjusting both the pressure within the system, and tuning the wavelength of the shorter-wavelength seed. Furthermore, the impressive high-power handling capability of the AR-HCF may enable the scalability of the technique. This scalability may allow for increased output energy by elevating either the single pulse energy or the repetition rate of the pump laser. Various embodiments may be compatible with the abundant high-power ultrafast fiber lasers in the near-infrared region currently available in the market. This compatibility may offer a clear pathway toward realizing an all-fiber-based femtosecond laser source capable of generating high-energy tunable MIR pulses.

[0067] Various embodiments may offer immense promise for advancing various applications reliant on high-power MIR radiation, marking a significant leap forward in the field.

[0068] FIG. 3 shows (a) a schematic of a system for generating a mid-infrared (MIR) light; and (b) a scanning electron micrograph of a cross-section of an antiresonant hollow-core fiber (AR-HCF) according to various embodiments. The system may include a first laser source 302 configured to provide an infrared light (2 μm pump). The system may also include a second laser source 304 configured to provide a further light (NIR seed) having a wavelength shorter than a wavelength of the infrared light provided by the first laser source 302. The system may additionally include an optical element 306 (i.e., a dichroic mirror or DM) configured to combine the infrared light provided by the first laser source 302 and the further light provided by the second laser source 304 into a combined light. The system may also include a first gas cell 308 configured to hold a gas, and a second gas cell 310 configured to hold the gas. The

system may additionally include a hollow core fiber (HCF) 312 in fluidic communication with the first gas cell 308 and the second gas cell 310 such that the hollow core fiber 312 is also configured to hold the gas. The hollow core fiber 312 when filled with the gas may be configured to emit the mid-infrared (MIR) light (i.e., MIR signal) in response to the combined light being provided to the hollow core fiber 312, the mid-infrared (MIR) light having a wavelength in a mid-infrared range. The second laser source 304 and the optical element 306 may be removed if the first laser source 302 can generate the required further light by itself, i.e., via self-spectral broadening of the infrared light (2 μm pump) generated by the first laser source 302.

[0069] The conversion to MIR may take place inside the gas-filled HCF 312 through a DFWM process. The 2 μm pump may be synchronously injected with NIR seed into the 30 cm-long HCF 312. The two beams may be combined through the dichroic mirror 306, which may have a high reflection below 1.7 μm and a high transmission above 1.7 μm. The fiber 312 may be placed extending between the pair of gas cells 308, 310 that are pressurized with argon.

[0070] A delay line 314 in the pump arm may control the temporal overlap between the pump and the seed. A set of half-wave plates (HWP) 316a, 316b and polarizers (P) 318a, 318b may be in both the pump arm and the seed arm to adjust the energy in each beam. The output spectrum may be recorded by an intensity-calibrated monochromator 320. The system may also include a mirror (M) 322 configured to direct the further light (NIR seed) towards the dichroic mirror 306, and a collimate lens (L) 324 configured to collimate the combined light for transmission to the hollow core fiber 312. The first gas cell 308 may be configured (e.g., by having transparent window 308a) to allow the combined light to pass through to the hollow core fiber 312, and the second gas cell 310 may be configured (e.g., by having transparent window 310b) to allow the mid-infrared (MIR) light from the hollow core fiber 312 to pass through to a further collimate lens (L) 326. 308b denotes a part of the gas cell 308 that is configured to hold a first end of the hollow core fiber 312, while 310a denotes a part of the gas cell 310 that is configured to hold a second end of the hollow core fiber 312. A further mirror 328 may be configured to direct the MIR light from the further collimate lens 326 to the monochromator 320. A pressure controller 330 may be used to control or adjust the pressure of the gas in the hollow core fiber 312.

[0071] The AR-HCF as shown in FIG. 3(b) may be used as the HCF 312 to achieve low loss and high efficiency. This fiber may have a core diameter of 126 μm and a dielectric

cladding thickness of 2.2 μm, designed to position the pump laser within the third transmission band. The thickness of the cladding may be one parameter that determines the transmission spectrum in the AR-HCF. As highlighted above, the pump laser operates at 2 μm, while the seed laser operates at a central wavelength of 1.35 μm under a pressure of 20 bar. These conditions may satisfy the phase matching requirements and may lead to the generation of a MIR wavelength centered at 3.6 μm.

[0072] Within the context of AR-HCF, the cladding can be approximated as an arrangement of layers with high and low refractive indices. Each higher refractive index layer may be visualized as a Fabry-Perot resonator, and the resonator may either enhance or decrease the confinement of light within the hollow core, depending on the resonant (high-loss) or anti-resonant (transmission) conditions. The resonance condition can be expressed as:

$$\lambda_m = \frac{2n_1 d}{m}\sqrt{\left(\frac{n_2}{n_1}\right)^2 - 1} \quad (1)$$

where n_1 and n_2 are low and high material refractive indices, respectively; d is the thickness of the high-index layer; and m is an integer, representing the order of resonance. In other words, there are the first, second, and third transmission and resonance bands when m is equal to 1, 2, and 3, respectively. When resonance wavelengths are reached, the core mode leaks through the high-index layer, whereas when the wavelength is away from the resonance, the high-index layer confines the light within the hollow core region. As a result, the spectral transmission may reveal several broad transmission bands that are separated by high-loss bands. By precisely designing the fiber wall thickness at 2.2 μm, the pump of 2 μm may be positioned within the third transmission band, ensuring that the resulting MIR signals align with the second transmission band.

[0073] The conversion to MIR may be realized by exploiting the DFWM process in which three wavelengths interact within the medium, resulting in the generation of two new wavelengths. This process satisfies the conservation of photon energy and momentum:

$$2\omega_p = \omega_s + \omega_i \quad (2)$$

$$2\beta_p = \beta_s + \beta_i + \Gamma_{NL} \quad (3)$$

where ω_p , ω_s, and ω_i are the angular frequencies of the pump, signal, and idler photons involved in the DFWM process and β_p, β_s, and β_i are the wavevectors at the pump, signal, and idler, respectively. $\Gamma_{NL} = 2\gamma_p P$ is the nonlinear correction term and can be tuned by changing pressure P, where γ_p is the nonlinear coefficient at ω_p.

[0074] In the system shown in FIG. 3(a), the structure of the hollow core fiber 312, the central wavelength of the pump laser, the central wavelength of the seed laser, and the pressure may collectively determine the phase matching conditions described in Equation (2) and Equation (3), which in turn dictate the targeted MIR wavelength. These parameters can be controlled to tune the desired MIR wavelength. The pump laser can be adjusted within the range of 1 μm to 2.5 μm, and the seed laser can be adjusted within the range of 0.6 μm to 1.7 μm. By varying these parameters, corresponding MIR signals can be generated spanning from 2.5 μm to 10 μm. Additionally, adjusting the pressure may allow for more precise tuning of the MIR central wavelength. The fiber 312 used may be any type of hollow core fiber with a diameter ranging from 60 μm to 140 μm, enabling the transmission of targeted wavelengths with relatively low loss.

[0075] FIG. 4A shows (a) a plot of input spectral intensity (in arbitrary units or a.u.) / output spectral intensity (in arbitrary units or a.u.) as a function of wavelength (in micrometers or μm) illustrating the output spectrum of the mid-infrared (MIR) light (solid line) generated by the system under pressure of 20 bar argon with pump laser (dotted line) having energy of 50 μJ and seed laser (dashed line) having energy of 1 μJ according to various embodiments; and (b) a plot of phase mismatch $\Delta\beta$ (in per centimeter or /cm) as a function of wavelength (in micrometers or μm) illustrating the corresponding degenerate four-wave mixing (DFWM) phase matching diagram according to various embodiments. In FIG. 4A(a), TB1, TB2, and TB3 represent the first, second, and third transmission bands. The pump at 2 μm falls in the third transmission band (TB3) of the fiber. TB1 and TB2 may be located in mid-IR. In FIG. 4A(b), dashed lines indicate signal and idler at 1.39 μm and 3.56 μm, respectively, while dotted lines represent signal and idler at 1.28 μm and 4.57 μm, respectively.

[0076] The experimental results depicted in FIG. 4A(a) showcase several key findings. As mentioned above, the dotted and dashed lines represent the pump and seed spectra at 50 μJ and 1 μJ, respectively, with the pump at 2 μm falling in the third transmission band of the fiber. The solid line illustrates the output spectrum of the system under 20 bar argon pressure. Notably, seeding a weak signal at 1.3 μm initiates DFWM, resulting in emission at 3.56 μm. The energy in the 3–4 μm band, measured directly using a long-pass filter and a power meter, totals 7 μJ, corresponding to a remarkable 14% energy conversion from the pump. This is a seven-fold increase in the mid-IR pulse energy compared to a previous demonstration that relied on the band-edge effect of the anti-resonant hollow-core fiber. It is worth highlighting

that this may represent the highest MIR energy generated through a nonlinear frequency conversion process in gas-filled AR-HCF to date.

[0077] Another emission band observed at 4.57 μm may arise due to both a DFWM phase matching as well as a band-edge-induced soliton-dispersive wave phase matching. The interaction between the 1.3 μm seed and 2 μm pump photons may facilitate DFWM, enhancing the 4.57 μm emission (vertical dotted line). The wavelength of the MIR light generated may increase with the decrease in the wavelength of the seed. This intriguing phenomenon may hold potential for further exploitation in generating high-energy MIR sources towards longer wavelengths exceeding 5 μm.

[0078] In FIG. 4A(b), the phase mismatching satisfying Equations (2) and (3) with the pump at 2 μm, is depicted. The two vertical dashed lines represent the phase-matched signal/idler at 1.39 μm and 3.56 μm, respectively. From Equations (2) and (3), there may be zero phase-mismatch for signal and idler at 1.39 μm and 3.56 μm, respectively, which agrees with experimental results. The 1.35 μm seed pulse may have a sufficient bandwidth to provide the 1.39 μm signal photons.

[0079] FIG. 4B shows a plot of input spectral intensity (in arbitrary units or a.u.) / output spectral intensity (in arbitrary units or a.u.) as a function of wavelength (in micrometers or μm) illustrating (i) the output spectrum of the mid-infrared (MIR) light generated by the system under pressure of 20 bar argon with pump laser having energy of 50 μJ and seed laser having energy of 1 μJ according to various embodiments as shown in FIG. 4A(a); and (ii) the output spectrum of the mid-infrared (MIR) light generated by the system without the seed laser according to various embodiments. For the TB2 energies, it may be emphasized that even when seed injection was blocked, a significant MIR signal may still be generated. This may occur because as the pump pulse propagates through the gas-filled hollow-core fiber, nonlinear effects such as self-phase modulation may broaden the pulse spectrum. This spectral broadening may inherently provide a seed signal, thereby initiating the degenerate four-wave mixing process.

[0080] FIG. 5 illustrates characterization of the mid-infrared pulses at 3 μm - 4 μm range: (a) a plot of intensity (in arbitrary units or a.u.)/chirp (in radians per pico-seconds or rad/ps) as a function of delay (in femto-seconds or fs) illustrating the intensity (solid line) and phase (dotted line) profiles of the mid-infrared pulses according to various embodiments; (b) a plot of spectrum (in arbitrary units or a.u.) as a function of wavelength (in micro-meters or μm)

illustrating the measured spectrum (solid line) and reconstructed spectrum (dashed line) according to various embodiments; and (c) plots of wavelength (in micrometers or μm) as a function of delay (in femtoseconds or fs) showing acquired (left) and reconstructed (right) spectrograms according to various embodiments. The fullwidth at half-maximum duration of the MIR is 42 fs.

[0081] The wavelength of the MIR light or radiation may be influenced by both the fiber structure and gas pressure. FIG. 6 shows (a) a plot of intensity (in arbitrary units or a.u.) as a function of wavelength (in micro-meters or μm) illustrating the output spectrum of the mid-infrared (MIR) light generated by the system under pressure of 11 bar (solid line), 17 bar (dashed line) and 23 bar (dotted line) according to various embodiments; and (b) a plot of phase mismatch $\Delta\beta$ (in per centimeter or /cm) as a function of wavelength (in micro-meters or μm) illustrating the corresponding degenerate four-wave mixing (DFWM) phase matching diagram according to various embodiments. As the pressure increases, the phase matching points for DFWM shift towards longer wavelengths, consequently leading to a corresponding shift in the generated MIR signals towards longer wavelengths. In other words, the wavelength of the mid-infrared (MIR) light may increase with pressure. FIG. 6 may portray the remarkable tunability of the generated MIR signals, underscoring how adjustments in system pressure may offer precise control over emitted wavelengths. This tunability may not only enhance the versatility of the system, but may also unlock a multitude of potential applications across diverse fields.

[0082] Various embodiments may serve as a versatile frequency-down conversion module that can seamlessly integrate immediately at the output of a near-infrared femtosecond fiber laser. The compact integration may enable the construction of an all-fiberized ultrafast MIR source boasting a small footprint, robust performance in challenging environments, and exceptional beam quality.

[0083] This technological advancement may be poised for widespread adoption beyond laboratory settings, particularly in driving high-power mid-infrared (MIR) supercontinuum generation. The resulting high-power MIR supercontinuum may enhance the identification of molecular "fingerprints" with unprecedented sensitivity. This breakthrough may hold transformative potential, enabling early disease diagnosis based solely on blood or exhaled breath samples. Moreover, the applications of various embodiments may extend into critical environmental and security sectors. Various embodiments may enable real-time monitoring of pollutants, remote sensing of toxic chemicals and explosives, and/or enhance combat

identification and countermeasure capabilities. Additionally, various embodiments may promise advancements in the medical field, allowing for cellular-scale surgeries with minimal collateral damage. The adaptability and precision of the system according to various embodiments may offer a significant leap forward in advancing these critical areas of research and application.

Claims

1. A system for generating a mid-infrared (MIR) light, the system comprising:
   a first laser source configured to provide an infrared light having a wavelength selected from a range from 1 μm to 2.5 μm;
   a second laser source configured to provide a further light having a wavelength shorter than the wavelength of the infrared light provided by the first laser source;
   an optical element configured to combine the infrared light provided by the first laser source and the further light provided by the second laser source into a combined light;
   a first gas cell configured to hold a gas;
   a second gas cell configured to hold the gas; and
   a hollow core fiber in fluidic communication with the first gas cell and the second gas cell such that the hollow core fiber is also configured to hold the gas;
   wherein the hollow core fiber when filled with the gas is configured to emit the mid-infrared (MIR) light in response to the combined light being provided to the hollow core fiber, the mid-infrared (MIR) light having a wavelength in a mid-infrared range.

2. The system according to claim 1,
   wherein the mid-infrared (MIR) light comprises mid-infrared (MIR) pulses.

3. The system according to claim 1 or claim 2,
   wherein the wavelength of the mid-infrared (MIR) light is inversely proportional to the wavelength of the further light.

4. The system according to any one of claims 1 to 3,
   wherein the wavelength of the mid-infrared (MIR) light is of a value selected from a range from 2.5 μm to 10 μm.

5. The system according to any one of claims 1 to 4,
wherein the wavelength of the mid-infrared (MIR) light is of a value selected from a range from 3 μm to 4 μm.

6. The system according to any one of claims 1 to 5,
wherein the wavelength of the further light is of a value selected from a range from 0.6 μm to 1.7 μm.

7. The system according to any one of claims 1 to 6,
wherein the further light is a near infrared (NIR) light.

8. The system according to any one of claims 1 to 7,
wherein the wavelength of the mid-infrared (MIR) light is directly proportional to a gas pressure of the gas in the hollow core fiber.

9. The system according to any one of claims 1 to 8,
wherein the hollow core fiber is an antiresonant hollow core fiber.

10. The system according to any one of claims 1 to 9,
wherein a diameter of a core of the hollow core fiber is of a value selected from a range from 60 μm to 140 μm; and
wherein a thickness of a cladding of the hollow core fiber is of a value selected from 1.2 μm to 3.2 μm.

11. The system according to any one of claims 1 to 10,
wherein the mid-infrared (MIR) light is generated via degenerate four-wave-mixing (DFWM).

12. The system according to any one of claims 1 to 11,
wherein the optical element is a dichroic mirror, a wavelength-division multiplexer, a dispersion grating, or a cube beam splitter.

13. The system according to any one of claims 1 to 12, further comprising:

a delay line arranged either along a first optical path or along a second optical path.

14. The system according to claim 13, further comprising:

a first set of optical elements arranged along the first optical path for controlling an input energy of the infrared light provided by the first laser source; and

a second set of optical elements arranged along the second optical path for controlling an input energy of the further light provided by the second laser source.

15. The system according to claim 14,

wherein the first set of optical elements comprises a half-wave plate and a polarizer; and

wherein the second set of optical elements comprises a half-wave plate and a polarizer.

16. The system according to claim 14 or claim 15, further comprising:

a mirror along the second optical path, the mirror configured to direct the further light towards the optical element.

17. The system according to any one of claims 1 to 16, further comprising:

a focus or collimate lens configured to focus the combined light onto within the hollow core fiber or collimate the combined light for transmission.

18. A method of forming a system for generating a mid-infrared (MIR) light, the method comprising:

providing a first laser source configured to provide an infrared light having a wavelength selected from a range from 1 μm to 2.5 μm;

providing a second laser source configured to provide a further light having a wavelength shorter than the wavelength of the infrared light provided by the first laser source;

providing an optical element configured to combine the infrared light provided by the first laser source and the further light provided by the second laser source into a combined light;

providing a first gas cell configured to hold a gas;

providing a second gas cell configured to hold the gas; and

arranging a hollow core fiber to be in fluidic communication with the first gas cell and the second gas cell such that the hollow core fiber is also configured to hold the gas;

wherein the hollow core fiber when filled with the gas is configured to emit the mid-infrared (MIR) light in response to the combined light being provided to the hollow core fiber, the mid-infrared (MIR) light having a wavelength in a mid-infrared range.

19. The method according to claim 18,

wherein the mid-infrared (MIR) light comprises mid-infrared (MIR) pulses.

20. The method according to claim 18 or claim 19,

wherein the wavelength of the mid-infrared (MIR) light is inversely proportional to the wavelength of the further light.

21. The method according to any one of claims 18 to 20,

wherein the wavelength of the mid-infrared (MIR) light is of a value selected from a range from 2.5 μm to 10 μm.

22. The method according to any one of claims 18 to 21,

wherein the wavelength of the mid-infrared (MIR) light is of a value selected from a range from 3 μm to 4 μm.

23. The method according to any one of claims 18 to 22,

wherein the wavelength of the further light is of a value selected from a range from 0.6 μm to 1.7 μm.

24. The method according to any one of claims 18 to 23,
wherein the further light is a near infrared (NIR) light.

25. The method according to any one of claims 18 to 24,
wherein the wavelength of the mid-infrared (MIR) light is directly proportional to a gas pressure of the gas in the hollow core fiber.

26. The method according to any one of claims 18 to 25,
wherein the hollow core fiber is an antiresonant hollow core fiber.

27. The method according to any one of claims 18 to 26,
wherein a diameter of a core of the hollow core fiber is of a value selected from a range from 60 μm to 140 μm; and
wherein a thickness of a cladding of the hollow core fiber is of a value selected from 1.2 μm to 3.2 μm.

28. The method according to any one of claims 18 to 27,
wherein the mid-infrared (MIR) light is generated via degenerate four-wave-mixing (DFWM).

29. The method according to any one of claims 18 to 28,
wherein the optical element is a dichroic mirror, a wavelength-division multiplexer, a dispersion grating, or a cube beam splitter.

30. The method according to any one of claims 18 to 29, further comprising:
arranging a delay line either along a first optical path or along a second optical path.

31. The method according to claim 30, further comprising:

arranging a first set of optical elements along the first optical path for controlling an input energy of the infrared light provided by the first laser source; and

arranging a second set of optical elements along the second optical path for controlling an input energy of the further light provided by the second laser source.

32. The method according to claim 31,

wherein the first set of optical elements comprises a half-wave plate and a polarizer; and

wherein the second set of optical elements comprises a half-wave plate and a polarizer.

33. The method according to claim 31 or claim 32, further comprising:

providing a mirror along the second optical path, the mirror configured to direct the further light towards the optical element.

34. The method according to any one of claims 18 to 33, further comprising:

providing a focus or collimate lens configured to focus the combined light onto within the hollow core fiber or collimate the combined light for transmission.