Abstract: A laser system comprising: (i) a pulsed light source generating a pulsed light having an optical spectrum centered at a source wavelength; (ii) a Raman conversion fiber coupled to the pulsed light source, wherein the pulsed light traverses the nonlinear Raman conversion fiber and is converted by a cascaded Stimulated Raman Scattering process into a first pulsed light output corresponding to last Stokes order and having an optical spectrum centered at a first output wavelength which is longer than the source wavelength; and (iii) a harmonic generator operatively coupled to said a Raman conversion fiber to accept the first pulsed light output order and to convert it to longer optical frequency such that said harmonic generator producing light output in the final output wavelength situated in the 150-775 nm range.
For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.
PULSED UV AND VISIBLE RAMAN LASER SYSTEMS

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

[0001] This application claims the benefit of U.S. Provisional Application No. 60/795,915, filed April 28, 2006, entitled "Pulsed UV and Visible Raman Laser Systems", and U.S. Provisional Application No. 60/810,520, filed June 2, 2006, entitled "Laser Systems for Producing UV and Visible Light Output."

[0002] The present invention relates generally to solid state lasers and more particularly to fiber lasers using nonlinear wavelength conversion to produce output in the ultra violet (UV) and/or visible wavelength ranges.

TECHNICAL BACKGROUND

[0003] Coherent light sources in the visible (400-775 nm) wavelength range and in the UV or deep UV (DUV) range (150-400 nm) find a number of important applications (such as in medicine, life sciences, material processing, photolithography and metrology). Typically, a high output power is desired and different output wavelengths are required for different applications.

[0004] However, in contrast to the widely available light sources developed for the near-IR spectral ranges, the choice of the shorter wavelength light sources (e.g., visible or UV) is very limited. Excimer lasers are often utilized to produce UV radiation at 248 nm, 193 nm, and 157 nm. However, these lasers are expensive, costly to maintain, have relatively poor beam quality, and are not tunable.
[0005] Harmonic conversion in nonlinear crystals is typically used to convert the IR (infra red) wavelength output of the diode pumped solid state (DPSS) laser to UV and visible ranges. Unfortunately, only a few discrete wavelengths are available from DPSS lasers, and therefore, the output wavelengths that are produced by this method are also limited to harmonics (e.g., 2\textsuperscript{nd}, 3\textsuperscript{rd}, 4\textsuperscript{th}) of the fundamental or pump wavelengths. Such laser outputs are, for example, 532nm, 355nm, and 266nm that are produced by harmonic conversion of 1064 nm Nd:YAG laser output.

[0006] Optical Parametric Oscillator (OPO) may be utilized with a DPSS laser to provide additional output wavelength tunability, provided that a nonlinear crystal with a suitable transparency range and phase matching conditions exists. This is not always possible. Furthermore, because the output wavelength from OPO is determined by phase matching conditions of the nonlinear crystal, the laser systems utilizing OPOs are generally complex, and suffer from poor stability, as compared to the laser systems that utilize harmonic converters.

[0007] An additional disadvantage of DPSS lasers is that the average power output is limited to relatively low (10-25W) values by thermal issues (heat dissipation in the laser crystal). To achieve high peak optical power values required for efficient nonlinear frequency conversion, they are typically operated either in Q-switched (long, 30-50 ns pulses) regime where the pulse repetition frequencies are limited to several kHz, or in a mode-locked (5-10 ps pulses) regime where the spectral width of the output is significantly larger, and therefore coherence length of the laser output is shorter then that of a continuous wave or CW laser. Therefore, such DPSS lasers are not suitable for producing quasi-CW output, where optical pulses are sufficiently long to keep the high coherence, but at the same time repetition frequency is high enough so that for a particular detector the output light appears effectively CW.

[0008] A new class of diode-pumped lasers, rare earth doped glass fiber lasers, has recently attracted much attention and is finding its first industrial uses. Due to long
(meters) length of the active medium, fiber lasers do not suffer from heat dissipation issues as much as DPSS lasers and are therefore capable of providing much higher average power output, keeping a perfect single transverse mode beam quality. Thus, fiber lasers are perfect candidates for creating high power CW or quasi-CW sources in visible and UV ranges by harmonic conversion, hi addition, the fiber laser output wavelength is not limited to a discrete value and can be tuned in a relatively broad range, for example ~1030-120 nm for Yb-doped devices. However, even with this additional flexibility, not all of the desired output wave-lengths can be reached by harmonic generation. OPOs may be utilized to provide additional wavelengths, but, as stated above, laser systems utilizing OPOs are generally complex, and suffer from poor stability, as compared to the laser systems that utilize harmonic converters.

[0009] Therefore, a need still exists to develop high power, efficient and stable quasi-CW laser sources in the 0.15-0.775 µm range.

SUMMARY OF THE INVENTION

[00010] One embodiment of the invention is a Raman laser system comprising: a pulsed light source generating a pulsed light having an optical spectrum centered at a source wavelength; (ii) a Raman conversion fiber coupled to the pulsed light source, wherein the pulsed light traverses the nonlinear Raman conversion fiber and is converted by a cascaded Stimulated Raman Scattering process into a first pulsed light output having an optical spectrum centered at a first output wavelength which is longer than the source wavelength; and (iii) a harmonic generator operatively coupled to said Raman conversion fiber to accept the first pulsed light output and to convert it to higher optical frequency such that said harmonic generator is producing the final light output at the final output wavelength situated in the 150-775 nm range.

[00011] One embodiment of the invention is a laser system that comprises: a light source generating a light, said light source comprising a fiber laser or fiber amplifier operating in a visible spectral range; and a frequency converter operatively coupled to the
light source to accept the light provided by the light source and to convert it to higher optical frequency such that the frequency converter is producing light output in the final output wavelength situated in the 150-400 nm range. Preferably the final output wavelength is situated in the 150-300 nm range.

[00012] Additional features and advantages of the invention will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein, including the detailed description which follows, the claims, as well as the appended drawings.

[00013] It is to be understood that both the foregoing general description and the following detailed description present embodiments of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated into and constitute a part of this specification. The drawings illustrate various embodiments of the invention, and together with the description serve to explain the principles and operations of the invention.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[00014] FIG. 1 is a block diagram view of the pulsed cascaded Raman laser system 10 according to one embodiment of the present invention;

[00015] FIG. 2 is a plot (produced by numerical modeling) of optical power versus fiber length, for pump light, one intermediate Stokes order and output light, in accordance with some aspects of the present invention;

[00016] FIG. 3A is a plot of conversion efficiency versus fiber length;
FIG. 3B shows optical pulse shapes at different points within the fiber for conversion into the second Stokes order in accordance with some embodiments of the present invention;

FIG. 4 is a spectrum graph of the output of the 38 m long nonlinear Raman converter fiber pumped by 400 ps long light pulses with the spectrum centered at the source wavelength of 1064 nm produced by a Nd:YAG pulsed laser system;

FIG. 5 illustrates schematically first example of the laser system according to the present invention;

FIG. 6 illustrates schematically one embodiment of the pulsed laser source (MOPA) utilized in the laser system of FIG. 5;

FIG. 7 illustrates schematically second example of the laser system according to the present invention;

FIG. 8 illustrates schematically third example of the laser system according to the present invention;

FIG. 9 illustrates schematically fourth example of the laser system according to the present invention;

FIG. 10 illustrates schematically fifth example of the laser system according to the present invention;

FIG. 11 illustrates schematically sixth example of the laser system according to the present invention; and
FIG. 12 illustrates schematically seventh example of the laser system according to the present invention.

FIGS 13A and 13B are block diagrams of two embodiments of another laser system according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Sub-200 nm laser light sources are very important for metrology applications in the semi-conductor industry. As the feature sizes of integrated circuits are shrinking, shorter wavelength light is used for a photolithography. Mask and wafer inspection, as well as optics manufacturing is then in need of the same or similar DUV light wavelength. The systems presented used, based on solid-state laser sources, harmonic conversion and OPOs typically work at very low repetition rates, are very bulky, complex, expensive and require frequent and complicated maintenance.

A new class of diode-pumped lasers, rare earth doped glass fiber lasers, has recently attracted much attention and is finding its first industrial uses. Due to long (meters) length of the active medium, fiber lasers do not suffer from heat dissipation issues as much as DPSS lasers and are therefore capable of providing much higher average power output, keeping a perfect single transverse mode beam quality. Thus, fiber lasers are perfect candidates for creating high power CW or quasi-CW sources in visible and UV ranges by harmonic conversion. In addition, the fiber laser output wavelength is not limited to a discrete value and can be tuned in a relatively broad range, for example about 570-630 nm for Sm-doped lasers or amplifiers. This tunability provides for tuning or adjustment of the final output wavelength provided by the laser system.

A non-cavity or non-resonant method and apparatus for generating coherent light are taught herein. In accordance with some embodiments of the present invention, cascaded stimulated Raman scattering (SRS) of pulsed pump radiation in an optical fiber with preferably normal (negative) dispersion is used in the inventive method and apparatus.
to result in multiple order wavelength shifts of initially shorter wavelength towards longer wavelengths.

[00031] A harmonic generation (e.g., 2\textsuperscript{nd}, 3\textsuperscript{rd} or 4\textsuperscript{th}) is then utilized to convert the power output of the last Stokes order to higher optical frequency (shorter wavelengths), such that the harmonic generator produces light output at the final output wavelength situated in the 150-775 nm range.

[00032] Reference will now be made in detail to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. Whenever possible, the same reference numerals will be used throughout the drawings to refer to the same or like parts. One embodiment of the laser system of the present invention is shown in FIG. 1, and is designated generally throughout by the reference numeral 10.

[00033] Referring to FIG. 1, laser system 10 includes a pulsed light source 102, (for example, a "master oscillator - power amplifier" (MOPA) that includes the initial "master oscillator" pulsed light source 102') that generates a pulsed light 104 having an optical spectrum centered at a source wavelength $\lambda_p$. A Raman wavelength converter 106 comprising a nonlinear Raman conversion fiber 106' is operatively coupled to the pulsed light source 102. The pulsed light 104 traverses the nonlinear Raman conversion fiber 106', and is converted into a first pulsed light output signal 108 having an optical spectrum centered at an output wavelength $\lambda_{out}$ (which is longer than the source wavelength $\lambda_p$) by a cascaded Stimulated Raman Scattering process, such that the output wavelength $\lambda_{out}$ corresponds to the N-th Stokes order (N= 1, 2, 3 or 4) of the source wavelength $\lambda_p$ for a glass material of the nonlinear Raman conversion fiber 106', and a significant portion (> 25%) of the optical power from the pulsed light source 102 is converted into the N-th Stokes order in a single pass through the nonlinear Raman conversion fiber 106'. The pulse width at the peak pulse power provided by the pulsed light source 102 as well as the Raman conversion fiber length, and the dispersion parameter of this fiber should be preferably chosen to maximize conversion of the source...
power to the power output of the last Stokes order at the output wavelength in a single pass through the nonlinear Raman conversion fiber 106'.

[00034] More specifically, the Raman wavelength shifting in optical fibers is utilized to produce coherent light output at any wavelength where the glass material used to make the fiber is transparent. Multiple-order stimulated Raman scattering (SRS) generation, where the i-th Stokes order of the initial wavelength serves as a pump for generation of the (i+1)-th Stokes order is utilized as a cascaded wavelength converter (from shorter to longer wave-lengths) for accomplishing a significant wavelength shift within a transparency window of the glass material used to make the optical fiber, resulting in producing a new output wavelength $\lambda_{out}$ that might be not available from other types of laser sources.

[00035] Due to the self-phase matched nature of the stimulated Raman scattering process, if light pulses with a high enough peak power are launched and propagated in a single-mode optical fiber 106% consecutive conversion to the 1st, 2nd, 3rd and so on Stokes orders of the pump light wavelength (i.e., source wavelength) $\lambda_p$ will take place. The distance in spectrum or optical frequency between pump and Stokes orders is determined by the so-called Stokes shift (or the wavelength (frequency) shift at which the Raman gain in a particular glass material the optical fiber 106' is made of) is maximum. Since conversion happens consecutively, which of the Stokes orders is present at the Raman conversion fiber's output is uniquely determined by the input peak power and fiber length. An additional degree of control can be executed by creating a wavelength-dependent loss (for example, by bending the fiber), so that the conversion stops at a given Stokes order. The Raman conversion fiber 106' may be a single nonlinear fiber having a uniform chromatic dispersion throughout the fiber length, such that the chromatic dispersion is normal for the source wavelength, the output wavelength, and every wavelength of a plurality of intermediate Stokes orders. The value of the chromatic dispersion at each of the source, output and intermediate Stokes wavelength is determined, at least in part, by the requirement to minimize nonlinear optical effects detrimental to the conversion efficiency including spectral broadening caused by four-wave-mixing and by the
requirement to minimize pulse walk-off for any two consecutive conversion orders (wavelengths). Preferably the fiber length of the Raman conversion fiber 106' is determined from the peak pulse power of a source and the Raman gain, attenuation and effective area of the fiber, such that the stimulated Raman scattering threshold is overcome for N consecutive Stokes orders but is not overcome for (N+1) order resulting in source power converted mostly into the N-th order.

[00036] Alternatively, the Raman conversion fiber 106' may be made by a serial connection of nonlinear Raman fiber segments, each having normal chromatic dispersion for a particular subset of the input, output, and intermediate Stokes orders wavelengths that are traversing the particular fiber segment, and the value of the chromatic dispersion at each of the wavelengths of the subset is determined by the requirement to minimize nonlinear optical effects detrimental to the conversion efficiency including spectral broadening caused by four-wave-mixing and the requirement to minimize pulse walk-off for any two consecutive conversion orders (wavelengths). Preferably, each fiber segment has a fiber segment length, and the fiber segment length is predetermined from the peak pulse power of the first Stokes order entering that segment and Raman gain, attenuation and effective area of the fiber segment such that the stimulated Raman scattering threshold is overcome for those Stokes orders that are generated and traverse that particular segment, and the last fiber segment length is just sufficient to overcome N-th Stokes threshold but not sufficient to overcome (N+1) Stokes threshold resulting in source power converted mostly into the N-th order.

100037] A harmonic generator 110 is operatively coupled to the nonlinear Raman conversion fiber 106' to accept the first pulsed light output signal 108 at the wavelength \(\lambda_{i_{\text{in}}}\) and to convert it to higher optical frequency such that the harmonic generator 110 is producing the final pulsed light output 112 at the wavelength \(\lambda_{\text{out}}\) situated in the 150-775 nm range. The harmonic generator 110 may be, for example, 2\(^{nd}\), 3\(^{rd}\), or 4\(^{th}\), etc. harmonic generator, which means that it is converting the first output wavelength \(\lambda_{i_{\text{out}}}t\) to the final wavelength of \(\lambda_{\text{out}} = \lambda_{i_{\text{out}}}t/2; \lambda_{i_{\text{out}}}t/3, \) or \(\lambda_{i_{\text{out}}}t/4\).
The Raman conversion of the pulsed light takes place in a single pass through
the optical fiber 106' and does not require any resonant cavities or wavelength-selective
elements. However, for such a free-running conversion, each subsequent Stokes order will
have a slightly broadened spectrum, since the Raman gain spectrum in glass is relatively
broad and the generation of a new Stokes order takes place by amplification of a
spontaneous Raman emission. Additional spectral broadening takes place due to the
influence of four-wave mixing. For these reasons, the precise selection of the output
wavelength may be difficult. Therefore, we suggest that the seed light is preferably
provided at the Raman-fiber input for the first pulsed light output wavelength \( \lambda_{\text{out}} \) and
(optionally) for each intermediate Stokes wavelengths. This is illustrated, for example, in
FIG. 1, where the seed light sources 112 (for the first pulsed light output) and 114 (for one
of the intermediate Stokes orders) are shown. In principle, it is sufficient to provide only a
few microwatt of power in each seed, but providing higher power (up to 10 mW) will
result in a shorter Raman fiber length required, slightly higher conversion efficiency and
less noise. Neither pulsed light source 102 (also referred to as a pump herein), nor the
lasers seeding intermediate Stokes orders 114 are required to have a very narrow spectral
output, due to a relatively weak wavelength dependence of Raman gain (less than 1 nm is
generally sufficient), and can have multiple longitudinal mode structure. The seed source
112 for the first output wavelength \( \lambda_{\text{out}} \) preferably provides a narrow spectral line, and
more preferably single-frequency. Since it will be amplified by a stimulated Raman
scattering, the spectral width of the output of the Raman wavelength converter 106 will be
nearly the same as the spectral width of the seed source 112. Thus, having a narrow line,
highly coherent seed source 112 (preferably less than 100 pm linewidth) will ensure that a
high conversion efficiency can be reached in the harmonic conversion stages. External
cavity, DFB, DBR or vertical cavity semiconductor diode lasers are most suitable, but a
single-frequency DFB or DBR fiber lasers, as well as solid state lasers, can also be used as
a first output seed source 112.

[00038]
Because the Raman process is polarization selective, it is important that all of the pump 102 and seed sources 112, 114 are polarized, and their output polarization states are aligned at the input of the Raman converter fiber 106'. It is also preferable that the Raman converter fiber 106' is polarization-preserving, otherwise, a combination of the half-wave and quarter-wave plates will be required to correct the ellipticity of the converter output and align its polarization in respect to the optical axes of the nonlinear crystals utilized in a harmonic generator (converter) 110. As is well known in the art, an optical birefringence property of the nonlinear crystals is commonly used to achieve phase matching, or ensure that light of different harmonics propagates at the same speed through the crystal.

The Raman converter 106 has to be designed according to the type of Raman conversion fiber 106' used. Our numerical calculations and preliminary experiments indicate that silica-based fiber 106' has a sufficiently large Raman gain to achieve high conversion efficiency in a relatively short length, as will be described below. Depending on the desired peak and average power level, the fiber might need to be designed to have a large mode area, to avoid optical damage. The Raman gain for a silica-based fiber has two closely spaced peaks, approximately at 13.4 and 14.6 THz from the optical frequency of the pump (i.e., the pulsed light source 102). It is preferable that the pump wavelength λp, intermediate Stokes, and the output seed wavelengths are chosen such that the distance between any consecutive two in optical frequency domain is between 12.5 and 14.7 THz, and more preferably at exactly the maximum of the Raman gain for a given converter fiber.

According to the embodiments, the pulse width provided by the light source 102 is 0.1 to 100ns and a duty cycle of the pulse is 1:2 to 1:1000. For optimum efficiency, it is important to consider the requirements for the optical pulse width and repetition frequency. In principle, there is no upper limit on the optical pulse width. However, for pulses longer than a few nanoseconds, stimulated Brillouin scattering (SBS) in the fiber can limit the maximum amount of power that can be converted and one has to make sure
that the pump optical spectrum is broad enough to suppress SBS. Also, to increase the nonlinear conversion efficiency in crystals, it is desirable that the duty cycle (the ratio of pulse width and repetition period, which is also the ratio of average to peak power) is less than 1:100, which, for pulses longer than 10 ns, will limit the repetition frequency to values lower than 1 MHz, which is not desirable if the goal is to produce a quasi-CW source. On the other hand, if the optical pulses are too short, then the Raman conversion efficiency will be affected by the walk-off in time between pump and Stokes orders caused by fiber dispersion. Therefore, unless a Raman conversion fiber is specially designed to match group velocities of pump and Stokes orders light, it is preferable not to have pulses shorter than 300 ps (0.3ps). Therefore, the preferred range for pulse width is 0.3-10 ns, with the corresponding repetition frequency range of 1-30 MHz. It is also preferable that the pulse shape is as close as possible to a perfect rectangle, since the presence of any pulse "wings" will cause an incomplete conversion. Another important consideration is the amount of spectral broadening imposed on the Raman converter output by a nonlinear optical effect known as self-phase modulation (SPM), which can be detrimental for the efficiency of the subsequent harmonic conversion. As is well known in the art, SPM only causes optical frequency change, resulting in spectral broadening, if the light intensity is changing in time. Therefore, a nearly perfect rectangular pulse, with the flat top and shortest possible rise and fall times, is preferred to minimize the influence of the SPM.

[00042] As herein defined, the term "nonlinear fiber" refers to an optical waveguide (including a fiber) having sufficiently large Raman gain, sufficiently long length, sufficiently low attenuation and sufficiently small effective area for the fundamental waveguide mode that the optical power threshold for generation of at least one (first) Stokes order does not exceed an optical damage threshold for the material the optical waveguide is made of.

[00043] An arbitrary large wavelength shift can be accomplished by a cascaded stimulated Raman scattering process, provided that a suitable glass material exists that is transparent (i.e., low loss, or loss that is smaller than 1/3 Raman gain provided but the
Raman fiber) and has sufficient Raman gain at the pump and all of the required Stokes orders wavelengths. Therefore, using a pulsed laser, Raman wavelength conversion process, and the appropriate harmonic generator, in principle any desired output wavelength, including those in the visible and UV ranges can be produced. The nonlinear Raman conversion fiber 106' may be manufactured from an optical glass transparent in the mid-infrared wavelength range, the glass being preferably made from a member selected from the group consisting of sulfides, selenides, tellurides, germanates (based on GeO₂), aluminates (based on Al₂O₃), and tellurites (based on TeO₂).

[00044] The output power of the laser system 10 is limited only by the optical damage to the glass used to make the Raman fiber 106' and can in principle reach several hundred watts. The choice of glass material to make the Raman fiber is dictated by the output wavelength and power requirements. Fused silica based material is preferred in the wavelength range of 800-1900 nm due to its high transparency and optical damage thresholds and Raman gain sufficient to achieve efficient conversion in a relatively short fiber length. Other glass types may also be used if higher Raman gain or different wavelength range is desired.

[00045] Using pump pulses from the pulsed light source 102 with high peak power allows completing conversion in a relatively short length of Raman fiber 106'. The maximum theoretical power conversion efficiency is defined by the ratio of Raman fiber output 108 to the pump 104 photon energy, and therefore can approach (or even exceed) 90%. For example, for the conversion of 1056.3 nm pump wavelength λₚ into its second Stokes order at 1178 nm in silica fiber, the theoretical maximum efficiency is η = 1056/1178 = 0.897.

[00046] Optionally, a high-power optical amplifier 105 is coupled between the initial pulsed light source 102'(a pulsed master oscillator in this embodiment) and the nonlinear Raman conversion fiber 106' for amplifying the pulsed light 104 such that the average power and the peak pulse power of the pulsed light source 102 can be increased, hi this
way, cost-effective pump sources based on the well developed fiber amplifier technology for the amplifier 105 may be utilized. The high-power optical amplifier 105 in conjunction with the initial pulsed light source 102' forms the master oscillator power amplifier (MOPA). The method and apparatus of the present invention are especially suitable for pump sources including Yb-doped or Er-doped fiber optical amplifiers, but can also be used with other pump sources having other types of power amplifiers 105. More specifically, it is noted that a Yb-doped fiber based laser or MOPA can provide an optical output in the 1030 to 1120 nm range and Er, Tm and Nd-doped silica fiber based lasers or MOPAs are capable of providing an output in 1530-1610 nm, 1800-2000 nm, and 890-930 nm ranges, respectively.

[00047] According to some embodiments of the present invention the light source 102 includes a tunable laser for tuning the source wavelength $\lambda_0$, wherein the tuning of the source wavelength provides fine tuning of the final output wavelength $\lambda_{\text{out}}$.

[00048] Due to a very long (several ms) lifetime of the excited states, rare-earth (e.g., Er or Yb) doped fiber amplifiers essentially amplify the average power of the incoming signal, and for a very small duty cycle, an amplifier 105 with only a modest average power output can produce very large peak pulse power. For example, 1 ns long pulses from a master oscillator 102% (e.g., a directly modulated distributed feedback (DFB) laser diode) can be amplified to a peak power of 20 kW in a multiple-stage Er or Yb-doped amplifier 105, while the average output power of power amplifier 105 is only 2 W, if the repetition rate is 100KHz (peak power is 1000X average power). With such a large peak power, efficient Raman conversion could be performed in only a few meters length of silica-based fiber.

[00049] Directly modulating a semiconductor laser diode with an electrical pulse generator or connecting the diode output to an separate electro-optic intensity modulator for setting the pulse width, can be used to make the initial pulsed light source 102' for generating the pulsed light 104, with or without further amplification (i.e. with or without
the optional amplifier 105). As noted above, forming, a rectangular pulse is preferred for maximizing the conversion efficiency (minimizing the effect of incomplete conversion in the pulse wings) and minimizing spectral broadening (by self-phase modulation (SPM)). Since Er, Yb, Tm and Nm-doped amplifiers 112 have a relatively wide spectral gain bandwidth (several 10s of nanometers), the pulsed light source 102 and to some extent the whole laser system 10 can be made wavelength tunable by using a tunable master oscillator pulse source 102' (such as an external cavity semiconductor laser, directly modulated or coupled to a separate modulator).

To illustrate the sequential nature of the cascaded Raman wavelength conversion, FIG.2 shows the results of the simplified numerical modeling based on the coupled power equations presented in the paper by G.Vareille, O.Audouin, E.Desurvire, Electronics Letters, 1998, v.34, No. 7, p.675 and parameters typical of a single-mode silica based fiber. In the model, a pulsed light nature of the source 102 is neglected (for simplification) and instead 1000W of continuous wave (CW) pump power at a source wavelength λp of 1056.3 nm is directly provided at the input of a nonlinear Raman conversion fiber, along with the small amount (10^-6 W) of seed power for the 1st and 2nd Stokes orders. FIG. 2 is a plot of optical power versus the length of the Raman conversion fiber 106'. As shown in FIG. 2, the output optical power at the pump wavelength λp is fully converted to the 1st Stokes order at the wavelength of 1114 nm before the conversion step to the 2nd order starts. The plot also demonstrates that approximately, 12.5 m fiber length is required for each conversion step and all power is converted into the 2nd Stokes order (an output wavelength λ_out of 1178 nm) at 25 m length, with 90% efficiency. The conversion is accomplished in a single pass through the fiber and, due to its non-resonant nature and the self-phase-matched nature of the Stimulated Raman Scattering, is largely unaffected by the variations in fiber dispersion, attenuation or effective area along its length. Thus, the operation of the pulsed cascaded Raman wavelength converter 106 is advantageously robust to variations in dispersion, loss and effective area of the nonlinear Raman conversion fiber 106'.
[00051] It is important for the understanding of the present invention to discuss requirements for the chromatic dispersion of the nonlinear Raman conversion fiber 106. The main requirement for the operation of the pulsed cascaded Raman wavelength converter 106 is that the nonlinear Raman conversion fiber 106 has normal (negative) dispersion at any point along its length, at least for the wavelengths of the source \( \lambda_p \), first output \( \lambda_{j_{\text{out}}} \) and any of the intermediate Stokes orders that are traversing this point. Normal (negative) dispersion is needed to prevent nonlinear optical effects detrimental to the cascaded Raman conversion efficiency, such as pulse break-up caused by soliton effects, spectral line broadening caused by four-wave mixing, amplification of noise and spontaneous emission by a parametric or modulational instability effect and generation of "parasitic" spectral lines.

[00052] Known techniques of fiber waveguide design can be used to ensure that the fiber dispersion is normal (negative). Standard doped or micro-structured fiber, where the cladding contains a number of holes running along the fiber length, can be used.

[00053] It is difficult to define the minimum absolute value of fiber dispersion that is still sufficient for suppression of detrimental nonlinear effects discussed above, since it depends on many factors including the rise and fall times of the pump pulses. In modern optical communication systems, it is usually believed that about 2-3 ps/nm/km of dispersion is enough to suppress four-wave mixing. However, the power levels used in optical transmission are usually much less than those discussed here. Therefore, the present invention teaches that it is preferable if the fiber dispersion is more negative than -5 ps/nm/km. It is preferable that fiber dispersion be in -10 to -100 ps/nm/km range.

[00054] On the other hand, the absolute value of the nonlinear Raman conversion fiber dispersion can not be allowed to be too large to avoid the "dispersion walk-off" in time. "(i.e., separation of light pulses at different wavelengths due to dispersion) of the light pulses of different Stokes orders, causing conversion efficiency decrease and pulse shape distortion. The allowable value depends on the pulse width and the length of fiber required.
for one conversion step to be completed (12.5 m in the example of FIG. 2), but in general it is preferred that the amount of walk-off is less than 10% of the pulse width.

[00055] We have performed a preliminary analysis of the feasibility of obtaining both high conversion efficiency and high average output power in the Raman converter 106 described above. An optical fiber 106' was manufactured with pure silica cladding and 22 \( \mu \text{m} \) diameter core slightly doped with GeO\(_2\), so that the difference between core and cladding refractive index or index delta is 0.0007. A numerical model of the Raman converter 106 took into account the time dependence of the light intensity, nonlinear optical effects such as self and cross-phase modulation and four-wave mixing and accepts the actual measured parameters of the fiber such as, for example, effective modal area, chromatic dispersion and Raman gain. FIGS 3A and 3B present the modeling results for laser system 10 that comprises a pulse light source 102 providing 400 ps long optical pulses with 100 ps rise and fall times and 25 kW peak power. We assumed that seed source 112, 114, etc., provides 1.0 mW of CW power for all Stokes orders up to the 4th. FIG. 3A illustrates dependence of the average power (averaged over the duty cycle) in the 2\(^{nd}\) Stokes order on the position within the fiber 106'. As is evident from FIG. 3A, almost 80% average power conversion efficiency to the second Stokes wavelength can be reached for the 26 m long fiber 106'. For the conversion to 3\(^{rd}\) Stokes order, the model predicts maximum 69% average power conversion efficiency for the 36 m fiber length (not shown). FIG. 3B shows the 2\(^{nd}\) Stokes order signal pulse shapes at different positions in the fiber. It can be concluded that peak power conversion efficiencies are even higher than the above percentages because, as can be seen from the FIG. 3B, the wavelength converted pulses become slightly shorter and more rectangular than input pulses, due to the incomplete conversion in the pulse wings.

[00056] Experiments were also performed, pumping the Raman conversion fiber 106' with 400 ps long 1064 nm pulses from a Nd:YAG laser. FIG. 4 presents the output pulsed signal spectrum at the end of the nonlinear Raman conversion fiber 106' for the fiber length of 38 meters. As explained above, the choice of fiber length for the given input
pulse peak power uniquely determines at which Stokes order (2\textsuperscript{nd} Stokes order for the case of FIG. 4) the conversion will stop. FIG. 4 illustrates relative powers corresponding to the wavelengths of $\lambda_p$, 1\textsuperscript{st} Stoke and 2\textsuperscript{nd} Stoke, at the Raman conversion fiber's output. As can be seen from FIG. 4, the conversion efficiency from 1064 nm light provided by the Nd:YAG laser into the 2\textsuperscript{nd} Stokes is approximately 60\% (i.e., ≈4/7), although no seed light was provided for either 1\textsuperscript{st} or 2\textsuperscript{nd} Stokes, and the input pulse shape was close to a double exponential, very different from the optimum rectangle, which resulted in a noticeable amount of pump light ($\lambda p$) and 1\textsuperscript{st} Stokes light still present at the output. The measured 2\textsuperscript{nd} Stokes pulse energy was about 10 μJ, which means that the output pulse peak power was about 25 kW. For the duty cycle of 1:100, this would correspond to the average output power from the Raman converter 106 of 250 W. Based on the presented numerical and experimental results, it can be concluded that Raman wavelength conversion of the pulsed light signal into the 2\textsuperscript{nd} or 3\textsuperscript{rd} Stokes orders with multiple 100 W average and multiple 10s of kW peak output power, and conversion efficiency of greater than 50\% is entirely feasible. Stokes orders higher than 3\textsuperscript{rd} order can also be produced, but with progressively diminishing efficiency.

[00057] As already mentioned above, output wavelength range of approximately 1030-1120 nm is directly accessible for an Yb-doped fiber laser systems. With Raman wavelength conversion (by the Raman converter 106) to up to 3\textsuperscript{rd} Stokes order, this range can be effectively extended to 1030-1340 nm. Therefore, output wavelengths $\lambda_{out}$ in the 515-770 nm range can be produced by 2\textsuperscript{nd} harmonic generation, 343.3-446.7 nm by 3\textsuperscript{rd} harmonic generation, 257.5-335 nm by 4\textsuperscript{th} harmonic generation and so on. Other types of fiber laser systems, such as those including a silica based fiber which is Er-Yb co-doped for 1530-1570 nm range, Nd-doped for 890-930 nm range (working at the 3-level transition) or Tm-doped for 1800-2000 nm range, can also be utilized to pump Raman wavelength converters 106. The only requirement, according to this embodiment of the present invention, is the availability of a suitable narrow spectral line seed light source for the output wavelength of a corresponding Raman converter 106 (seeding intermediate Stokes wavelengths is not strictly required, although will improve conversion efficiency).
Additional output wavelengths $\lambda_{\text{out}}$ can be produced by sum frequency mixing, in a suitable nonlinear crystal, the outputs of two different fiber lasers, each one possibly followed by a Raman wavelength converter and harmonic generator. In accordance with the teachings of the present invention, any desired output wavelength $\lambda_{\text{out}}$ in the 150-775 nm range can be produced by a suitable combination of one or two pulsed fiber lasers, Raman converters, harmonic generators and sum-frequency mixing stages, as will be illustrated below.

[00058] In the following, we present examples of laser systems 10 producing some specific output wavelengths, of interest for specific applications. In the following exemplary embodiments, we choose to design harmonic generators 110 in such a way that they use exclusively borate nonlinear crystals (LBO, BBO, CLBO), which are known to have the highest optical damage thresholds and are therefore capable of producing higher powers by harmonic conversion. Those skilled in the art will appreciate that these examples represent only a small subset of the almost infinite number of possibilities opened by using Raman wavelength conversion technology and that other non-linear crystals may also be utilized.

[00059] Example 1: Laser system for producing a Sodium D2 line at $\lambda=589.16$ nm. Sodium beacons, created by exciting atomic sodium in the upper atmosphere, can be used as "guidestars" for adaptive optical systems and are therefore of great interest for advanced laser-based defense system applications. A high-power CW or quasi-CW sources tuned to the sodium D2 absorption line at the wavelength of 589.16 nm are required for this purpose.

[00060] An exemplary laser system 10 for producing an output at 589.16 nm is illustrated in FIG. 5. In the embodiment shown in FIG. 5, the pulsed light source 102 is an Yb-doped fiber system (master oscillator - power amplifier, or MOPA). This MOPA 102 is providing pulsed light at $\lambda_p=1056.3$ nm to the Raman converter 106. The pulsed 1056.3 nm light 104 is converted by the Raman converter 106 to a first output signal 108.
with the optical spectrum centered at a first output wavelength $\lambda_{iout} = 1178.32$ nm, via cascaded Stimulated Raman Scattering process. Since $\lambda_{iout} = 178.32$ nm corresponds to the second Stokes order wave-length of 1056.3 nm for the fused silica glass, the Raman converter 106 can advantageously use silica-based Raman conversion fiber 106' with low loss and high optical damage thresholds. The harmonic generator 110 is a 2nd harmonic generator comprising a nonlinear LBO (LiB$_3$O$_5$, lithium triborate) crystal IIoA and optional lenses HOA focusing the first light output 108 from the Raman converter 106 and collimating the final light output from the LBO crystal HOA. The 2nd harmonic generator 110 of this embodiment converts the first output wavelength $\lambda_{iout} = 1178.32$ nm to the final output wavelength of $\lambda_{out} = \lambda_{iout}/2 = 1178.32/2 = 589.16$ nm.

[00061] To design the laser system 10 to operate at the desired output wavelength $\lambda_{out}$ one can work the problem backwards. That is, from the available data on nonlinear crystals, it is known that $\lambda_{out} = 589.16$ nm can be generated in an LBO crystal HOA as a second harmonic of 1178.32 nm. Thus, it can be done if $\lambda_{iout} = 1178.32$ nm is available. From the data available on the Raman gain in silica-based optical fiber, it is known that 1178.32 nm is 2 Stokes shifts away from 1056.3 nm, which falls within the wavelength range accessible for the Yb-doped fiber laser systems. Therefore, the laser system with 589.16 nm output, according to the present invention, can be designed starting with the $\lambda_p = 1056.3$ nm Yb-doped MOPA. It is noted that if the required final output wavelength $\lambda_{out}$ is slightly different from 589.16 nm (for example, it is within 576 to 622 nm range), the Yb-doped MOPA can be tuned to provide the appropriate wavelength $\lambda_p$. More specifically, an Yb-doped MOPA can be tuned to provide the output in 1030 to 1120 nm range, which can be (2nd) Stokes shifted in silica fiber to 1152 to 1244 nm, respectively, which in turn corresponds to a respective range of $\lambda_{out}$ of 576 to 622 nm.

[00062] As described above in reference to FIG.1, for the example embodiment shown in FIG.5, a seed light for the Raman converter output wavelength, i.e. 1178.32 nm, has to be provided at the input of the Raman conversion fiber 106'. The corresponding seed light...
source 112 can be an external cavity diode laser, or a vertical cavity laser, or a solid state laser with preferably a single narrow spectral line output. To increase the conversion efficiency, a second seed light from a second seed light source 114 can also be optionally provided at the wavelength of the first Stokes order of 1114 nm. Since 1114 nm is within the wavelength range accessible for Yb-doped lasers, a second seed light source 114 can be an Yb-doped fiber laser with fiber Bragg grating reflectors, but of course other diode, fiber or solid-state lasers may also be utilized.

[00063] An exemplary design of MOPA (light source 102) of FIG. 5 is illustrated in FIG. 6. The initial light source 102' (master oscillator) includes a laser diode 102A' and an electro-optical modulator (EOM) 102B' for creating pulsed light 104 provided to the optical amplifier 105 (power amplifier). This modulator is utilized to form optical pulses and to set the pulse width. Laser diode 102A' of this embodiment is the fiber Bragg grating (FBG) stabilized CW diode laser emitting 100 mW at 1056.3 nm and EOM 102B' is a lithium niobate intensity modulator which is used to form 2 ns long pulses at the 2 MHz repetition rate (1:250 duty cycle). Assuming 6 dB insertion loss from the EOM 102', the average optical power at its output is reduced to 0.1 mW. The power amplifier portion of MOPA includes four fiber amplifier stages 105A-105D, two of the stages 105A and 105B utilize Yb-doped single mode polarization maintaining fiber and two of the stages 105C and 105D utilize Yb doped polarization maintaining double-clad fiber. Yb-doped fibers are pumped by 976 nm pumps to provide amplification. The first amplifier stage 105A provides an average power output of 30 mW, the second stage 105B amplifies it to 400 mW, the third stage 105C further amplifies it to 5W and the last stage 105D provides average optical power output of 140 W and peak optical output power of 35 kW in 2ns pulses at 2MHz repetition rate. Assuming that the modulator 102B' has greater than 5 GHz electrical bandwidth, it should be capable of producing nearly rectangular pulse shape with less than 100 ps rise and fall times. Narrowband optical filters 105E are inserted after each amplification stage 105A-105C except the last amplification stage 105D. The two filters following the single mode fiber stages 105A, 105B are constructed using an optical circulator and an FBG, and the last filter of stage 105D is a thin-film...
device within a free-space optical isolator, so that they simultaneously serve to isolate amplification stages from each other and to reduce the accumulation of spectrally broadband amplified spontaneous emission. Those skilled in the art will appreciate that many variations to this example design are possible —different fiber, different number of stages, different power, pulse width and repetition rate. Other types of CW light sources with external modulators or directly modulated diode lasers can be used as an initial light source for the MOPA.

[00064] The MOPA output, mixed with Raman seeds from seed sources 112, 114, is launched into a Raman converter fiber 106', as shown in FIG. 1. Wavelength conversion proceeds through the first Stokes order at 1114 nm to the output second Stokes order at 1178.32 ran. The frequency shift between pump and first Stokes, as well as the one between first and second Stokes, is chosen to be 14.69 THz, corresponding to one of the peaks of Raman gain in fused silica. Based on the modeling and preliminary experimental results described above, it is expected that at least 50% of the MOPA output power or 70 W will be converted into a single-frequency output at 1178.32 nm. As stated above, the first output signal 108 is then provided to the harmonic generator 110 which, in this embodiment, includes one LBO crystal HOA. (See FIG. 5.) LBO crystal IIOA is the second harmonic generator. The LBO crystal IIOA receives the first output wavelength 108A of 1178.32 ran from the Raman converter 106 and provides the desired wavelength 108B of 589.16 nm. More specifically, the LBO crystal temperature is tuned to 313K to achieve non-critical phase matching (so-called non-critical phase matching at 0°=90° is the most preferable kind since it allows maximum angular and spectral acceptance for second harmonic generation and is characterized by zero or nearly zero birefringent walk-off of the pump and second harmonic light beams, which allows using long crystals to achieve high conversion efficiency with moderate levels of peak power) for the second harmonic generation of 1178.32nm, with the effective nonlinearity coefficient value of 0.84pm/V.

[00065] Table I below, provides the summary of crystal's (LBO IIOA) parameters utilized in the laser system 10 of example 1.
Table I. Calculated phase matching parameters for the laser system 10 of FIG.5

<table>
<thead>
<tr>
<th>Crystal</th>
<th>LBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinear process</td>
<td>SHG</td>
</tr>
<tr>
<td>First input $\lambda$, nm</td>
<td>1178.32</td>
</tr>
<tr>
<td>Second input $\lambda$, nm</td>
<td>1178.32</td>
</tr>
<tr>
<td>Output $\lambda$, nm</td>
<td>589.16</td>
</tr>
<tr>
<td>Phase matching temperature, K</td>
<td>313</td>
</tr>
<tr>
<td>Phase matching angle $\theta$, degrees</td>
<td>90</td>
</tr>
<tr>
<td>Phase matching angle $\phi$, degrees</td>
<td>0</td>
</tr>
<tr>
<td>Effective nonlinearity $d_{eff}$, pm/V</td>
<td>0.84</td>
</tr>
<tr>
<td>Birefringent walkoff, mrad</td>
<td>~ 0</td>
</tr>
</tbody>
</table>

In Table I, as well as in all subsequent examples, the first row lists the type of the nonlinear crystal(s) used and the second the type of a nonlinear process the crystal is performing. Rows 3-5 list the output and two input wavelengths (for the case when the nonlinear process is a second harmonic generation, the two input wavelengths are the same). Row 6 provides the crystal temperature and rows 7-8 provide the propagation direction angles with respect to the crystal optic axes (LBO is a so-called bi-axial crystal) required for phase matching. Row 9 specifies the effective nonlinearity coefficient (a measure of how efficient the conversion can be for a given input power and crystal length), and row 10 provides the input and output beam angular walk-off (slight angular separation of the input light and the harmonic light within the crystal) caused by crystal birefringence.

[00066] The non-critical phase matching (NCPM) at $\theta=90^\circ$ (and $\phi=0^\circ$, for bi-axial crystals) is the most preferable kind since it allows maximum angular and spectral acceptance (deviation of propagation direction and wavelength allowable without significant degradation of the conversion efficiency) for second harmonic generation and is characterized by zero or nearly zero birefringent walk-off of the pump and second harmonic light beams, which allows using long crystals to achieve high conversion efficiency with moderate levels of peak power.
The calculation of phase-matching angles and temperatures, as well as effective nonlinearity coefficients of borate crystals for this and subsequent examples was performed using SNLO, a free software package from Sandia National Labs. It is expected that the second harmonic generation efficiency can reach at least 50%, resulting in 35 W output at 589.16 nm wavelength. With further increase of the MOPA output power, and/or higher Raman conversion efficiency, building laser systems that provide an average output power greater than 50 W in the sodium D2 line is feasible.

Example 2: Laser system I for producing an output at $\lambda=198.7$

Sub-200 nm laser light sources are very important for metrology applications in the semiconductor industry. As the feature sizes of integrated circuits are shrinking, shorter wavelength light is used for a photolithography. Mask and wafer inspection, as well as optics manufacturing is then in need of the same or similar DUV light wavelength. The systems presently used, based on solid-state laser sources, harmonic conversion and OPOs, typically work at very low repetition rates, are very bulky, complex, expensive and require frequent and complicated maintenance.

FIG.7 presents an example of a 198.7 nm laser system **10** according to one embodiment of the present invention. As can be seen from the figure, 1067.6 nm Yb-doped fiber MOPA **102** pumps the Raman wavelength converter **106** which, in accordance with the design principles disclosed above, produces a narrow linewidth output at the 2nd Stokes wavelength $\lambda_{\text{out}}$ of 1192.2 nm. For this case, if the 1st Stokes order wavelength is 1126.5 nm, the Stokes frequency shift is 14.67 THz and corresponds to one of the Raman gain peaks in fused silica. The first output signal **108** from the Raman wavelength converter **106** is then provided to the harmonic generator **110** which, in this embodiment, includes two LBO crystals **HOA, HOB** and a BBO (beta barium borate, $\text{P-BaB}_2\text{O}_4$) crystal **HOC**. The three nonlinear crystals, LBO **HOA**, LBO **HOB** and BBO **HOC**, are used to generate a 6th harmonic of the 1192.2 nm wavelength by: (i) second harmonic generation (SHG) via LBO **HOA** producing wavelength of 596.1 nm, (ii) another SHG (LBO **HOB** producing the 298.05 nm wavelength), (iii) and sum-frequency mixing (SFM) of 596.1
and 298.05 via BBO HOC producing 198.7 nm output. More specifically, LBO crystals HOA and HOB are second harmonic generators (SGHs). The LBO crystal HOA receives the first output wavelength \( \lambda_{\text{out}} \) of 1192.2 nm from the Raman converter 106 and provides 596.1 nm output to the second LBO crystal HOB. Any residual light at 1192.2 nm wavelength is filtered out of the system by filter (dichroic mirror) HOD. The LBO crystal HOB receives the light at 596.1 nm and converts part of it (1 to 90%, preferably 50%) to 298.05 nm light. This 298.05 nm light, exiting the LBO crystal HOB together with the residual 596.1 nm light (99% to 10%), is then provided to the BBO crystal HOC which generates, via sum frequency mixing (SFM), light at the desired wavelength \( \lambda_{\text{out}} = 198.7 \) nm. As predicted by the SNLO software, the optimum temperature for the first LBO crystal HOA is 304 Kelvin. At this temperature, the crystal operates in non-critical phase matching (for light propagating at the angles of \( \theta = 90^\circ \) and \( \phi = 0^\circ \) to the optic axes of the crystal) with the effective nonlinearity coefficient of \( d_{\text{eff}} = 0.84 \) pm/V and essentially zero birefringent walk-off for the second harmonic generation of 1192.2 nm. The second LBO crystal HOB can not be non-critically phase matched. For the light propagating at \( \theta = 90^\circ \) and \( \phi = 64.6^\circ \) to the optic axes, the phase matching temperature for the second harmonic generation of 596.1 nm is 453 K (180 Celsius), the effective nonlinearity is \( d_{\text{eff}} = 0.4 \) pm/V and the birefringent walk-off is 14 milliradians. The BBO crystal HOC is a uni-axial crystal. For light propagating at \( \theta = 81.3^\circ \) to its optic axis, the phase-matching crystal temperature is 453 K, the effective nonlinearity is \( d_{\text{eff}} = 0.59 \) pm/V and the birefringent walk-off is 29.2 milliradians, for the nonlinear process of sum frequency mixing of 596.1 and 298.05 nm. Table II provides the summary of crystal's parameters utilized in the laser system 10 of example 2.

[00070] Table II- Calculated phase matching parameters for crystals in laser system 10 of FIG.7

<table>
<thead>
<tr>
<th>Crystal</th>
<th>LBO</th>
<th>LBO</th>
<th>BBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinear process</td>
<td>SHG</td>
<td>SHG</td>
<td>SFM</td>
</tr>
<tr>
<td>First input ( \Box ), nm</td>
<td>1192.2</td>
<td>596.1</td>
<td>596.1</td>
</tr>
<tr>
<td>Second input ( \Box ), nm</td>
<td>1192.2</td>
<td>596.1</td>
<td>298.05</td>
</tr>
</tbody>
</table>
Note: BBO is a uni-axial crystal, so only one phase matching angle is listed for it in Table II.

Also shown in FIG. 7 are (i) the two lenses L1 and L2 associated with each nonlinear crystal, one to focus the beam to a waist size optimal for maximizing conversion efficiency for a given crystal and another to re-collimate the output, (ii) a dichroic mirror M that removes unused 1192.5 nm light, (iii) a custom waveplate WP; and (iv) a harmonic separation optics set HOE. The optimal waist size for the beam focusing depends on the peak power of the light being converted, the length and the optical damage threshold of the crystal, the amount of birefringent walk-off and other parameters, and can be determined from modeling or in the experiment. The waveplate WP is custom designed to rotate either (but only one of) the 596.1 nm or 298.05 nm light polarization by 90° so that they are the same at the input of the BBO crystal. The harmonic separation optics set HOE is used to separate output 198.7 nm from both 596.2 and 298.1 and usually includes one or several prisms made of dispersive glass. For simplicity, those additional optical elements are not shown in optical schematics given for the remaining examples. Those skilled in the art will be able to determine where and when such elements should be used.

The advantage of the laser system 10 of FIG. 7 is that a minimum number of nonlinear crystals (only 3) are used to produce the sub-200 nm output. However, it may exhibit a significant birefringent walk-off in the BBO crystal HOC. Large walk-off does not allow tight focusing of the laser beams and therefore results in the lower conversion efficiency, since a shorter crystal or larger beams (lower optical power density) have to be used. The walk-off influence can be reduced if multiple 180° rotated crystals of the same kind are used, but is likely to reduce the useful lifetime of the device, because more
surfaces will be exposed to the high optical power. Diffusion or adhesive-free bonding can be utilized to eliminate additional exposed crystal surfaces by seamlessly joining the 180° rotated crystals together. From the numerical modeling estimates, the overall conversion efficiency, including Raman shifting, can reach 0.2% for a 100 W average, 25 kW peak power MOPA operating at 1:250 duty cycle (for example, 2 ns pulses at 2 MHz repetition rate, or 0.5 ns pulses at 8 MHz repetition rate), resulting in a 200 mW average power output at 198.7 nm.

[00073] Example 3: Laser system II for producing an output at λ=198.7 nm.
Another embodiment of the laser system 10 for producing 198.7 nm output is shown in FIG. 8. In this embodiment the pulsed light source 102 is a 1041 nm Yb-doped MOPA. This light source 102 pumps the Raman wavelength converter 106 producing its output λ_{out} at the 3rd Stokes wavelength of 1228.2 nm through intermediate 1096.7 (1st) and 1158.7 nm (2nd) Stokes orders (14.63 THz step). The harmonic generator 110 includes 4 stages, or 3 LBO crystals HOA, HOB, HOC and a CLBO (cesium lithium borate, CsLiB_{6}O_{10}) crystal HOD. Two LBO crystals HOA and HOB are used to consecutively produce 2nd (614.1 nm) and 4th (307.05 nm) harmonics of the Raman converter output by frequency doubling or SHG. The third LBO crystal HOC mixes the 1228.2 nm remaining light (10 to 90%, preferably 50%) at the output of the first LBO crystal HOA with its fourth harmonic (307.05 nm) from the output of the second one HOB by SFM (sum frequency mixing) to produce the light output at 245.64 nm (5th harmonic of 1228.2 nm). A second high-power amplification stage 102B is added to the MOPA to generate a second output at 1041 nm (the reason for having two separate high-power stages is to keep the peak power in each one below the nonlinear distortion and damage thresholds for the amplifier fiber), which is mixed with 245.64 nm light in the CLBO crystal to finally produce the output λ_{out} at 198.7 nm by SFM. Table III provides the summary of crystal's parameters utilized in the laser system 10 of example 3.

Table III- Calculated phase matching parameters for crystals utilized in Laser system 10 of FIG.8
Special care must be taken in the design of laser system 10 according to this embodiment of the present invention to ensure that different "color" (i.e., wavelengths) light pulses are aligned in time at the input of 3rd and 4th conversion stages (SFM), which in this embodiment correspond to LBO HOC and CLBO HOD. This can be done by carefully matching the optical path lengths, for example by introducing additional mirrors or plane-parallel glass blocks. In addition to the 198.7 nm output, the remaining 614.1, 307.05 and 245.64 nm light can be provided at the laser system output, if required by the application, or removed by filters, such as wavelength-selective (e.g., dichroic) mirrors or harmonic separators. Those skilled in the art will appreciate that in this and other examples, even with the exact same set of wavelengths, different nonlinear crystals can be used to perform the required conversion. For example, if ADA (ammonium dihydrogen arsenate, \(\text{NH}_4\text{H}_2\text{AsO}_4\)) crystal is used instead of LBO HOB in the 2nd stage (4th harmonic generation) and ADP (ammonium dihydrogen phosphate, \(\text{NH}_4\text{H}_2\text{PO}_4\)) crystal in the 3rd one (5th harmonic generation by SFM) instead of LBO HOC, both can be non-critically phase matched (i.e., \(\theta=90^\circ\) and \(\phi=0\) for bi-axial crystals) for the corresponding nonlinear process by temperature tuning. The laser system 10 of FIG. 8 is more complex than that of FIG. 7. It utilizes four instead of three crystals, and the Raman converter provides the 3rd and not 2nd Stokes order. The laser system 10 of FIG. 8 has, however, one very important advantage. The last crystal (CLBO) is much closer to the non-critical phase matching condition and therefore, birefringent walk-off is nearly negligible. In addition, a high peak IR (1041 nm) power is supplied to it directly from Yb-doped MOPA. This can
result in conversion efficiency in respect to UV power approaching 80%, and therefore minimum incoming UV power into the CLBO crystal will be needed to achieve the same DUV (deep UV) power output, thus minimizing optical damage to the CLBO crystal. It is noted that the optical power values as well as temperatures, phase matching angles, effective nonlinearity coefficient and birefringent walk-off values shown in FIG. 8 are given only as a guideline. Other configurations and operating temperatures may also be utilized. Based on the prediction of SNLO software, an output of 2 W at 198.7 nm can be produced from two arms of the Yb-doped MOPA delivering 100 and 32 W average power, respectively, which translates into an overall conversion efficiency of 1.5%, at least seven times higher than that of the laser system 10 of FIG. 7.

[00075] Example 4: Laser system III for producing an output at λ=198.7 nm.

[00076] The laser system 10 of FIG. 9 is similar to that of FIG. 8. It utilizes the same pulsed light source 102 and Raman converter 106 providing an output at the wavelength λ_{out} of 1228.2 nm, first and last crystals HOA, HOD. However, the 3rd harmonic (409.4 nm) of the Raman converter's 1228.2 nm output is produced by SFM mixing 2nd harmonic (614.1 nm) and original 1228.2 nm light in the LBO crystal HOB, and the 5th harmonic (245.64 nm) of the 1228.2 nm light is now produced by SFM mixing 2nd (614.1 nm) and 3rd (409.4 nm) harmonics in the CLBO crystal HOC. Due to higher effective nonlinearity for crystals HOB and HOC in the 2nd and 3rd conversion stages (values shown in Fig. 9) and higher power available at the input of the 2nd stage (i.e., into LBO crystal HOB), the overall conversion efficiency (predicted by numerical modeling) for the laser system 10 of this embodiment will have even higher (more than 2.1%) conversion efficiency than that of the laser system of FIG. 8, and should result in at least 3 W of 198.7 nm DUV light at the output of the 4th stage (CLBO HOD) of the harmonic converter 110. Table IV provides the summary of crystal's parameters utilized in the laser system 10 of example 4.

Table IV. Calculated phase matching parameters crystals used in laser system 10 of FIG.9

<table>
<thead>
<tr>
<th>Crystal</th>
<th>LBO</th>
<th>LBO</th>
<th>CLBO</th>
<th>CLBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinear process</td>
<td>SHG</td>
<td>SFM</td>
<td>SFM</td>
<td>SFM</td>
</tr>
</tbody>
</table>
Example 5: Laser system for producing an output at \( \lambda = 193 \) nm.

An embodiment of a 193 nm laser system 10 is illustrated in FIG. 10. The laser system 10 of this embodiment includes a pulsed light source 102 comprising one master oscillator and pre-amplifier and two high power optical amplifiers. More specifically, the output of the 1049.5 nm Yb-doped pre-amplifier is split and amplified separately by two high-power amplifiers. The first amplifier 1051 pumps a Raman converter 1061 producing 2nd Stokes signal at 1169 nm, and the second amplifier 1052 pumps another Raman converter 1062 producing 1st Stokes signal at 1106 nm. Several variations of the design are possible here, for example, a single Raman converter can be designed to produce output simultaneously at 1st and 2nd Stokes wavelengths, of course, with lower power. In the design shown, the same narrow line 1106 nm source can be used to seed the final output wavelength for second and the intermediate Stokes order for first Raman converter 1061. The 2nd harmonic of the 1169 nm light (584.5 nm) is generated in the first LBO crystal 110A by frequency doubling (SHG), and 3rd harmonic (389.7 nm) is generated in the second LBO crystal HOB by SFM. The 2nd and 3rd harmonics are mixed by SFM in the CLBO crystal HOC to produce the 5th harmonic at 233.8 nm. Finally, the 233.8 nm light is mixed with the output of a second Raman converter 1062 (1106 nm) in another CLBO crystal HOD to produce 193 nm output.

Table V provides the summary of crystal's parameters utilized in the laser system 10 of example 5.

<table>
<thead>
<tr>
<th>Crystal</th>
<th>1LBO</th>
<th>LBO</th>
<th>CLBO</th>
<th>CLBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>First input ( \lambda ), nm</td>
<td>1228.2</td>
<td>1228.2</td>
<td>614.1</td>
<td>1041</td>
</tr>
<tr>
<td>Second input ( \lambda ), nm</td>
<td>1228.2</td>
<td>614.1</td>
<td>409.4</td>
<td>245.64</td>
</tr>
<tr>
<td>Output ( \lambda ), nm</td>
<td>614.1</td>
<td>409.4</td>
<td>245.64</td>
<td>198.7</td>
</tr>
<tr>
<td>Phase matching temperature, K</td>
<td>290</td>
<td>453</td>
<td>453</td>
<td>453</td>
</tr>
<tr>
<td>Phase matching angle ( \theta ), degrees</td>
<td>90</td>
<td>90</td>
<td>71.4</td>
<td>85.7</td>
</tr>
<tr>
<td>Phase matching angle ( \phi ), degrees</td>
<td>0</td>
<td>22.9</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Effective nonlinearity ( d_{eff} ), pm/V</td>
<td>0.83</td>
<td>0.81</td>
<td>0.88</td>
<td>1.08</td>
</tr>
<tr>
<td>Birefringent walkoff, mrad</td>
<td>~0</td>
<td>12.4</td>
<td>23.8</td>
<td>6.5</td>
</tr>
</tbody>
</table>
Due to the fact that three out of four nonlinear crystals HOA, HOB, HOC, HOD are operated in non-critical phase matching, and all four crystals present relatively high effective nonlinear coefficients for the corresponding conversions, we expect that this design approach will be able to achieve the highest conversion efficiency (about 2.0%) of the previous four embodiments, resulting in as much as 4 W average power output at 193 nm starting with 200 W of ER power available from the two high power Yb-doped amplifiers 105i, 1052.

Example 6: Laser system II for producing an output at λ=193 nm.

Another embodiment of a 193 nm laser system 10 is illustrated in FIG. 11. In the laser system 10 of this embodiment the Yb-doped fiber MOPA 102 operating at λp=1041 nm provides pulsed light at this wavelength to the Raman converter 106. The Raman converter 106 then converts the light at wavelength λp to the 2nd Stokes order at λout = 1158 nm. The harmonic generator 110 comprises four nonlinear crystals —LBO HOA, LBO HOB, BBO HOC and CLBO HOD generating 2nd, 3rd, 5th and 6th harmonic of the 1158 nm wavelength by SHG and SFM, respectively. The final output 6th harmonic wavelength is λout = 193 nm. The calculated nonlinear conversion parameters are shown in Table VI. As can be seen from the table, the BBO crystal HOC operates with a significant birefringent walkoff which, depending on the power levels used, might necessitate using a short length of the crystal or elliptical beam focusing (with major axis of the ellipse along the walkoff direction), or both. Table VI provides the summary of crystal's parameters utilized in the laser system 10 of example 6.
Table VI. Calculated phase matching parameters for crystals of laser system 10 shown in FIG. 11

<table>
<thead>
<tr>
<th>Crystal</th>
<th>LBO</th>
<th>LBO</th>
<th>BBO</th>
<th>CLBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinear process</td>
<td>SHG</td>
<td>SFM</td>
<td>SFM</td>
<td>SFM</td>
</tr>
<tr>
<td>First input $\lambda$, nm</td>
<td>1158</td>
<td>1158</td>
<td>579</td>
<td>1158</td>
</tr>
<tr>
<td>Second input $\lambda$, nm</td>
<td>1158</td>
<td>579</td>
<td>386</td>
<td>231.6</td>
</tr>
<tr>
<td>Output $\lambda$, nm</td>
<td>579</td>
<td>386</td>
<td>231.6</td>
<td>193</td>
</tr>
<tr>
<td>Phase matching temperature, K</td>
<td>327</td>
<td>453</td>
<td>453</td>
<td>453</td>
</tr>
<tr>
<td>Phase matching angle $\theta$, degrees</td>
<td>90</td>
<td>90</td>
<td>58.4</td>
<td>80.4</td>
</tr>
<tr>
<td>Phase matching angle $\phi$, degrees</td>
<td>0</td>
<td>27.9</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Effective nonlinearity $d_{eff}$, pm/V</td>
<td>0.84</td>
<td>0.78</td>
<td>1.49</td>
<td>1.1</td>
</tr>
<tr>
<td>Birefringent walkoff, mrad</td>
<td>$\sim$ 0</td>
<td>14.4</td>
<td>79.8</td>
<td>14.6</td>
</tr>
</tbody>
</table>

[00082] Example 7: Laser system for producing an output at $\lambda$=195.1 nm.

In this example embodiment, two pulsed fiber-based MOPA sources are used — Nd-doped 102i operating at 913 nm (so-called 3-level transition for the Nd ions) and Yb-doped 102j operating at 1081 nm. The Nd-doped MOPA 102i pumps the Raman converter 106 producing the first output at 952 nm (1st Stokes order for 913 nm pump in silica fiber). The harmonic generator 110 comprises three nonlinear crystals. The first two crystals HOA and HOB are both LBO, generating respectively second (476 nm) and 4th (238 nm) harmonic of the Raman converter 952 nm output. The third crystal HOC is CLBO and it performs sum frequency mixing of the 238 and 1081 nm to produce the final output at 195.1 nm. The calculated nonlinear conversion parameters are specified in Table VII. Although this example embodiment uses the Nd-doped fiber MOPA system operating at the 3-level transition, which is more difficult to achieve than conventional 1064 nm 4-level transition operation, it has a significant advantage in that only three nonlinear crystals are used and they all are operated at or near the non-critical phase matching (NCPM) condition.

Table VII. Calculated phase matching parameters for the crystals of laser system 10 of FIG. 12

<table>
<thead>
<tr>
<th>Crystal</th>
<th>LBO</th>
<th>CLBO</th>
<th>CLBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinear process</td>
<td>SHG</td>
<td>SHG</td>
<td>SFM</td>
</tr>
</tbody>
</table>
It is noted that in the above examples the embodiments of laser system 10 do not utilize OPOs, thus producing stable outputs at the desired output wavelength. Furthermore, because the output wavelength from OPO is determined by phase matching conditions, and the embodiments of laser system 10 utilize Raman wavelength converters 106, laser systems 10 disclosed above do not need to produce phase matching prior to providing light to harmonic generator/ converter 110.

In accordance with other embodiments of the present invention, a visible light source is used in the inventive method and apparatus to provide light to the frequency converter that converts it to longer optical frequency such that the frequency converter produces light output in the final output wavelength situated in the 150-400 nm range. The visible light sources can be either a fiber laser or an optical amplifier (laser amplifier), and both are referred to as lasers sources or lasers herein.

Referring to FIGS. 13A, 13B, the laser system 10 of this embodiment includes a light source 102 which comprises a visible fiber amplifier or a visible fiber laser. The light source 102 may be, for example, a "master oscillator - power amplifier" (MOPA) that comprises the initial "master oscillator" pulsed light source 202' and an amplifier 206A. The laser system 10 may be a CW system (FIG 13B), or it may utilize an optional optical modulator 204A driven by an electrical pulse generator 102B that provides pulse modulation of the seed light entering the amplifier 206A (FIG. 1A).
In the embodiment of Figs. 13A and 13B the visible light fiber amplifier 206A comprises a Sm doped silica based fiber 206A'. The high-power optical amplifier 206A amplifies the (optionally pulsed) light 204 from the visible seed source 212. The frequency converter 210 is operatively coupled to the light source 202 (which in the embodiment of FIG. 13A is a pulsed light source, and is a CW source in the embodiment of FIG. 13B) to accept the light output 208A at the wavelength \( \lambda_{i_{\text{out}}} \) and to convert it to higher optical frequency, such that the frequency converter 210 is producing the final pulsed light output 212 at the wavelength \( \lambda_{\text{out}} \) situated in the 150–400 nm range. It is preferable that the light source 102 provides more than 10 W and preferably more than 20 W of optical power. The frequency converter 210 may be, for example, 2\text{nd}, 3\text{rd}, or 4\text{th}, etc. harmonic generator, which means that it is converting the first output wavelength \( \lambda_{i_{\text{out}}} \) to the final wavelength of \( \lambda_{\text{out}} - \lambda_{i_{\text{out}}}/2; \lambda_{i_{\text{out}}}/3, \text{ or } \lambda_{i_{\text{out}}}/4 \).

If the laser system 10 is a pulsed laser system, then fiber 206A' is operatively coupled to the pulsed light source 202', which includes the modulator 204A and the electrical pulse generator 204B. The high-power optical amplifier 206A amplifies the pulsed light 204 from the seed source 212, such that the average power and the peak pulse power of the pulsed light source 202 can be increased. The high-power optical amplifier 206A, in conjunction with the initial pulsed light source 202% form the master oscillator power amplifier (MOPA). The modulated pulsed light from the 594 nm seed source 212 enters the amplifier 206A, and the amplifier 206A generates amplified pulsed light output signal 208A having an optical spectrum centered at an output wavelength \( \lambda_{i_{\text{out}}} = 594 \text{ nm} \). According to the embodiment of the laser system of Fig. 13A, the pulse width provided by the light source 202 is 0.01 to 100 ns and a duty cycle of the pulse is 1:2 to 1:1000000, for example a pulse width of 0.1 to 80 ns, and a duty cycle of 1:2 to 1:10000. For optimum efficiency, it is important to consider the requirements for the optical pulse width and repetition frequency. In principle, there is no upper limit on the optical pulse width. However, for pulses longer than a few nanoseconds, stimulated Brillouin scattering (SBS) in the amplifier (or laser) fiber can limit the maximum amount of power that can be converted and one has to make sure that the pump optical spectrum is broad enough to...
suppress SBS. Also, to increase the nonlinear conversion efficiency in crystals, it is desirable that the duty cycle (the ratio of pulse width and repetition period, which is also the ratio of average to peak power) is less than 1:100, which, for pulses longer than 10 ns, will limit the repetition frequency to values lower than 1 MHz which is not desirable if the goal is to produce a quasi-CW source.

[00088] Due to a very long (several ms) lifetime of the excited states, rare-earth (e.g., Sm) doped fiber amplifiers essentially amplify the average power of the incoming signal, and for a very small duty cycle, an amplifier 206A with only a modest average power output can produce very large peak pulse power. For example, 1 ns long pulses from a master oscillator 202', (e.g., a directly modulated laser diode) can be amplified to a peak power of 20 kW in a multiple-stage Sm-doped (fiber) amplifier 206A while the average output power of power amplifier 206A is only 2 W, if the repetition rate is 100KHz (peak power is 10000x average power).

[00089] Directly modulating a semiconductor laser diode with an electrical pulse generator or connecting the diode output, as described above, to a separate electro-optic intensity modulator for setting the pulse width, can be used to make the initial pulsed light source 202' for generating the pulsed light. As noted above, forming, a rectangular pulse is preferred for maximizing the conversion efficiency (minimizing the effect of incomplete conversion in the pulse wings) and minimizing spectral broadening (by self-phase modulation (SPM)).

[00090] Since Sm₃Pr, or Eu amplifiers 206A have a relatively wide spectral gain bandwidth (several 10s of nanometers), the light source 202 and to some extent the whole laser system 10 can be is wavelength tunable or adjustable. Thus, according to some embodiments of the present invention the light source 202 includes a tunable laser for tuning the source wavelength, wherein the tuning of the source wavelength provides fine tuning or adjustment of the final output wavelength λₒ₁.
As already mentioned above, output wavelength range of approximately 575-625 μm is directly accessible for an Sm-doped fiber laser systems. Other types of fiber laser systems, such as those including a silica based fiber which is Dy doped for the output in the 550-600 nm range (and pumped by 425 inn ± 25 nm pump), as well as Pr and Eu-doped fiber lasers can also be utilized. Frequency converter 210, utilizing second, third or fourth harmonic generators can be utilized to provide the desirable output wavelength. For example, output wavelengths λ_{out} can also be produced by sum frequency mixing, in a suitable nonlinear crystal, the outputs from laser 106A and the first linear crystal 210A, or a SHG can be utilized in the crystal 210B to half the wavelength of light produced by the crystal 210A.

In the exemplary embodiments, we choose to design frequency converters 210 that utilize exclusively borate nonlinear crystals (LBO, BBO, CLBO), which are known to have the highest optical damage thresholds and are therefore capable of producing higher powers by harmonic conversion. Advantageously, these laser systems 10 achieve relatively high conversion efficiency, while avoiding or minimizing potential crystal damage caused by incident high power beams in short wavelengths (UV). This is done, at least partially, by minimizing the number of nonlinear crystals. Those skilled in the art will appreciate that these examples represent only a small subset of the almost many possibilities and that other non-linear crystals may also be utilized. As shown in Figs. 13A-13B, no OPOs were utilized in his embodiment of the laser system 10. Table VIII provides the summary of crystal's parameters utilized in the laser system 10 of Figures IA and IB. Preferably, no crystal exhibits more than 30 mrad, and more preferably no more than 25 mrad of birenfringent walkoff.

In Table VIII, as well as in all subsequent examples, the first row lists the type of the nonlinear crystal(s) used and the second the type of a nonlinear process the crystal is performing. Rows 3-5 list the output and two input wavelengths (for the case when the nonlinear process is a second harmonic generation, the two input wavelengths are the same). Row 6 provides the crystal temperature and rows 7-8 provide the propagation
direction angles with respect to the crystal optic axes (LBO is a so-called bi-axial crystal) required for phase matching. Row 9 specifies the effective nonlinearity coefficient (a measure of how efficient the conversion can be for a given input power and crystal length), and row 10 provides the input and output beam angular walk-off (slight angular separation of the input light and the harmonic light within the crystal) caused by crystal birefringence.

Table I- Calculated phase matching parameters for crystals in laser system 10.

<table>
<thead>
<tr>
<th>Crystal</th>
<th>SHG</th>
<th>SFG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinear process</td>
<td>LBO</td>
<td>BBO</td>
</tr>
<tr>
<td>First input λ, nm</td>
<td>594</td>
<td>594</td>
</tr>
<tr>
<td>Second input λ, nm</td>
<td>297</td>
<td>297</td>
</tr>
<tr>
<td>Output λ, nm</td>
<td>198</td>
<td>198</td>
</tr>
<tr>
<td>Phase matching temperature, K</td>
<td>433</td>
<td>433</td>
</tr>
<tr>
<td>Phase matching angle θ, degrees</td>
<td>90</td>
<td>82.9</td>
</tr>
<tr>
<td>Phase matching angle φ, degrees</td>
<td>65.4</td>
<td>N/A</td>
</tr>
<tr>
<td>Effective nonlinearity d_{eff}, pm/V</td>
<td>0.39</td>
<td>0.505</td>
</tr>
<tr>
<td>Birefringent walkoff, mrad</td>
<td>13.85</td>
<td>23.89</td>
</tr>
</tbody>
</table>

[00094] It is noted that a 594 nm output can be produced from Samarium or Dysprosium doped fiber lasers, and may also be provided by Praseodymium doped fluoride glass fiber lasers.

[00095] In the embodiments shown in FIGS. 13A and 13B, the light source 102 comprises a Sm-doped fiber laser, pumped by a blue broad area laser BAL(s), for example a blue GaN based laser (425 nm ±50 nm output). As stated above, other visible light fiber lasers, pumped by a shorter wavelength visible light pump sources may be utilized instead of Sm doped fiber laser. For example, Dy (pumped, for example by a 425 nm ±25 nm source), and Pr, or Eu doped fiber lasers 206A may also be used. In this embodiment the light source 202 is providing pulsed light at the wavelength λ_p=594 nm to the frequency converter 210. More specifically, the light source 102 may include an initial (optional oscillator or optionally pulsed) light source 202' and laser 206B operatively coupled to this light source 202'. The frequency converter 210 comprises a 2nd harmonic generator
based on nonlinear LBO (LiB$_3$O$_5$, lithium triborate) crystal 210A and a third harmonic generator based on BBO (beta barium borate, P-BaB$_2$O$_4$) crystal. The 2nd harmonic generator 210A of this embodiment converts the first output wavelength $\lambda_{out}=594$ nm to the 297 nm wavelength. The BBO crystal 210B then converts the 297 nm light and the remaining 595 nm light to the final output wavelength of $\lambda_{out}=198$ nm, via SFM (sum frequency mixing). Of course, if the 297 nm output is desired, the BBO crystal will not be needed, and the frequency converter would include only one nonlinear crystal, such as LBO 11QA, and a filter for filtering out the remaining 594 nm light.

[00096] Light source 102 advantageously has narrow line width output (1-1 000 pm) to increase conversion efficiency. It can be done, for example, by amplifying a lower power oscillator output with the high power amplifier.

[00097] More specifically, the temperature of the LBO crystal 210A is tuned to 433 K to achieve phase matching for the light propagating at angles =90 and =65.4 degrees to its optic axes for the second harmonic generation of 594 nm, with the effective nonlinearity coefficient value of 0.39 pm/V and a relatively small birefringent walk-off (14 mrad) between the pump and second harmonic light beams (which allows using long crystals to achieve high conversion efficiency with moderate levels of peak power). The temperature of the BBO crystal 210B is also tuned to 433 K, to achieve phase matching for the sum frequency mixing of the 594 nm and 297 nm light propagating at the 82.9 degrees angle to its optic axis (BBO is a uni-axial crystal). For this SFM process the amount of birefringent walk-off between the incoming 594 nm and 297 nm wavelength light and the output 198 nm third harmonic light is relatively small (22 mrad), which allows using longer crystals to achieve higher conversion efficiency with moderate levels of peak power. Advantageously, this embodiment minimizes the optical damage to the nonlinear crystals by high power laser beams by minimizing the number of crystal surfaces (it utilizes no more than 2 non-linear crystals) and by "trading" short wavelength power for long wavelength power (using less of the 297 nm and more of the 594 nm light power at the input of the BBO crystal to produce the same amount of 198 nm output).
It is noted that in the above examples the optical system 10 did not utilize OPOs, thus producing a more stable output wavelength $\lambda_{out}$ (since the output wavelength is a harmonic of the input one and is not determined by phase matching conditions).

It will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention. Thus it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.
What is claimed is:

1. A laser system comprising:
   a pulsed light source generating a pulsed light having an optical spectrum centered at a source wavelength;
   a nonlinear Raman conversion fiber coupled to the pulsed light source, wherein the pulsed light traverses the nonlinear Raman conversion fiber and is converted by a cascaded Stimulated Raman Scattering process into a first pulsed light output corresponding to last Stokes order and having an optical spectrum centered at a first output wavelength which is longer than the source wavelength; and
   a harmonic generator operatively coupled to said nonlinear Raman conversion fiber to accept the first pulsed light output order and to convert it to longer optical frequency such that said harmonic generator producing light output in the final output wavelength situated in the 150-775 nm range.

2. The laser system of claim 1, wherein most of the power provided by the pulsed light source is converted to the power output of the last Stokes order in a single pass through the nonlinear Raman conversion fiber.

3. The laser system of claim 1, wherein the pulsed light source has a pulse width of 0.1 to 100ns and a duty cycle of 1:2 to 1:1000.

4. The laser system of claim 1, wherein pulsed light source is a master oscillator power amplifier MOPA.

5. The laser system of claim 1, wherein 3 or less Stokes order shifts are utilized to provide said first output wavelength.
6. The laser system of claim 1, wherein the pulsed light source comprises a tunable laser for tuning the source wavelength, wherein the tuning of the source wavelength provides fine tuning of the final output wavelength.

7. The laser system of claim 1, wherein the nonlinear Raman conversion fiber comprises a single nonlinear fiber having a uniform chromatic dispersion throughout the fiber length, such that the chromatic dispersion is normal for the source wavelength, the output wavelength, and every wavelength of a plurality of intermediate Stokes orders.

8. The laser system of claim 1, wherein the nonlinear Raman conversion fiber comprises a wavelength-selective attenuation component of a wavelength band corresponding to a particular (N+l) Stokes order of the source wavelength, providing loss such that the threshold for that particular (N+l) order is never exceeded and cascaded Raman conversion ends at the Stokes order number N.

9. The laser system of claim 8, wherein the wavelength-selective attenuation component comprises a member selected from a group consisting of an absorbing dopant in the fiber, an absorption edge of glass material of the fiber, and a long-wavelength cutoff of a fiber waveguide.

10. The laser system of claim 8, wherein the wavelength-selective attenuator component comprises a discrete spectrally-selective filter element positioned at a point within the nonlinear Raman conversion fiber where the optical power of the output Stokes order N would otherwise reach the threshold for generation of order (N+l), thereby preventing generation of the order N+1.

11. The laser system of claim 1, further comprising a seed pump for injecting a small amount of CW or pulsed light into the nonlinear Raman conversion fiber, co-propagating along with the pulsed light from the pulsed light source, at one, several or
all of the intermediate Stokes and output wavelengths for "seeding" the Raman conversion to increase the Raman conversion efficiency.

12. The laser system of claim 4, further comprising a high-power optical fiber amplifier coupled in-between the nonlinear Raman conversion fiber and the pulsed light source for amplifying the pulsed light to increase and set the peak pulse power, wherein the high-power optical amplifier comprises an optical fiber doped with at least one rare-earth dopant member selected from a group consisting of Ytterbium, Erbium, and Thulium.

13. A pulsed cascaded Raman laser system comprising:

   a pulsed light source generating a pulsed light having pulses of approximately rectangular shape, the pulses having a peak pulse power and having an optical spectrum centered at a source wavelength; and

   a nonlinear Raman conversion fiber coupled to the pulsed light source,

   the nonlinear Raman conversion fiber manufactured from an optical glass transparent in the mid-infrared wavelength range, the glass made from a member selected from the group consisting of sulfides, selenides, tellurides, germanates (based on GeO$_2$), aluminates (based on Al$_2$O$_3$), and tellurites (based on TeO$_2$), wherein the pulsed light traverses the nonlinear Raman conversion fiber and the source power at the source wavelength is converted to an output power at an output wavelength in the infrared wavelength range by a cascaded Stimulated Raman Scattering process, the output wavelength longer than the source wavelength, such that most of the source power is converted to the power output of the last Stokes order in a single pass through the nonlinear Raman conversion fiber; and

   a harmonic generator operatively coupled to said nonlinear Raman conversion fiber to accept the power output of the last Stokes order and to convert it to longer optical frequency such that said harmonic generator producing light output in the final output wavelength situated in the 150-775 nm range.
14. A method for wavelength conversion and controlling the cascaded stimulated Raman scattering for wavelength conversion, the method comprising the steps of:

- generating a pulsed light having an optical spectrum centered at a source wavelength, wherein the pulsed light has a pulse width and a peak pulse power;
- coupling the pulsed light into and propagating through a nonlinear Raman conversion fiber for converting the source power at the source wavelength to a power output at an output wavelength longer than the source wavelength by a cascaded Stimulated Raman Scattering process, wherein the nonlinear Raman conversion fiber has a fiber length and a dispersion parameter;
- setting the pulse width, the peak pulse power, the fiber length, and the dispersion parameter for maximizing conversion of the source power to the power output of the last Stokes order at the output wavelength in a single pass through the nonlinear Raman conversion fiber; and
- coupling the light provided by the Raman conversion fiber into at least one harmonic generator to convert it to higher optical frequency such that said harmonic generator produces light output in the final output wavelength situated in the 150-775 nm range.

15. The method of claim 14, wherein the setting step comprises providing the nonlinear Raman conversion fiber having a uniform chromatic dispersion throughout its length, such that the chromatic dispersion is normal for the source wavelength, the output wavelength and every wavelength of an intermediate Stokes order, and the value of the chromatic dispersion at each of the source, output and intermediate Stokes wavelength is determined by the requirement to minimize nonlinear optical effects detrimental to the conversion efficiency including spectral broadening caused by four-wave-mixing and by the requirement to minimize pulse walk-off for any two consecutive conversion orders (wavelengths).
16. The method of claim 15, wherein the setting step comprises providing the nonlinear Raman conversion fiber having the fiber length determined from the peak pulse power of a source and the Raman gain, attenuation and effective area of the fiber such that the stimulated Raman scattering threshold is overcome for N consecutive Stokes orders but is not overcome for (N+1) order resulting in source power converted mostly into the N-th order.

17. The method of claim 14, wherein the setting step comprises providing a serial connection of nonlinear fiber segments, each having normal chromatic dispersion for a particular subset of the input, output, and intermediate Stokes orders wavelengths that are traversing the particular fiber segment, and the value of the chromatic dispersion at each of the wavelengths of the subset is determined by the requirement to minimize nonlinear optical effects detrimental to the conversion efficiency including spectral broadening caused by four-wave-mixing and the requirement to minimize pulse walk-off for any two consecutive conversion orders (wavelengths).

18. The method of claim 17, wherein each fiber segment has a fiber segment length, and the fiber segment length is predetermined from the peak pulse power of the first Stokes order entering that segment and Raman gain, attenuation and effective area of the fiber segment such that the stimulated Raman scattering threshold is overcome for those Stokes orders that are generated and traverse that particular segment, and the last fiber segment length is just sufficient to overcome N-th Stokes threshold but not sufficient to overcome (N+1) Stokes threshold resulting in source power converted mostly into the N-th order.

19. The method of claim 14, wherein the generating step comprises directly modulating a semiconductor laser diode using an electrical pulse generator, for setting the pulse width.

20. The method of claim 14, wherein the generating step comprises providing a continuous-wave (CW) laser source and an optical modulator for forming optical pulses and setting the pulse width.
21. The method of claim 14, wherein the generating step comprises generating pulses having an approximately rectangular shape.

22. A laser system comprising:
   a light source generating a light, said light source comprising is a fiber laser or fiber amplifier operating in a visible spectral range; and
   a frequency converter operatively coupled to said light source to accept the light provided by said light source and to convert it to higher optical frequency such that said frequency converter producing light output in the final output wavelength situated in the 150-400 nm range.

23. The laser system of claim 22, wherein light source is pumped by a visible light source.

24. The laser system of claim 22, wherein said laser system does not include an Optical Parametric Oscilator (OPO).

25. The laser system of claim 22 wherein said light source provides more than 10 W of optical power.

26. The laser system of claim 22 wherein fiber laser or fiber amplifier is adjustable.

27. The laser system of claim 22, wherein said light source is a pulsed light source and the light provided to said frequency converter is pulsed light.

28. The laser system of claim 22, wherein the pulsed light source has a pulse width of 0.1 to 100 ns and a duty cycle of 1:2 to 1:1000.

29. The laser system of claim 28, wherein pulsed light source is a master oscillator power amplifier MOPA.
30. The laser system of claim 22, wherein the pulsed light source comprises a tunable laser for tuning the source wavelength, wherein the tuning of the source wavelength provides fine tuning of the final output wavelength.

31. The laser system of claim 22, wherein said frequency converter includes no more than 2 nonlinear conversion crystals.

32. The laser system of claim 33, wherein said frequency converter includes at least one harmonic conversion crystal, to provide light in below 300 nm wavelength and none of said crystals exhibits more than 30 mrad walkoff.

33. The laser system of claim 29, further comprising a high-power optical fiber amplifier for amplifying the pulsed light to increase and set the peak pulse power, wherein the high-power optical amplifier comprises an optical fiber doped with at least one rare-earth dopant member selected from a group consisting of Samarium, Dysprosium, Europium and/or Praseodymium.

34. A laser system comprising:
   a light source generating a light, said light source comprising is a Sm doped fiber laser or a Sm doped fiber amplifier; and
   a frequency converter operatively coupled to said light source to accept the light provided by said light source and to convert it to longer optical frequency such that said frequency converter producing light output in the final output wavelength situated in the 150-300 nm range.

35. The laser system of claim 34 wherein said frequency converter utilizes no more than 2 nonlinear crystals.

36. The laser system of claim 34 wherein said frequency converter includes non linear crystals, and none of said crystals exhibits more than 25 mrad walkoff.
37. The laser system of claim 34 wherein at said frequency converter utilizes no more than 2 nonlinear crystals and said laser system does not include an Optical Parametric Oscilator (OPO).

38. The laser system according to claim 34, wherein said fiber laser of fiber amplifier is pumped by a visible light source.

39. The laser system according to claim 22, wherein said fiber laser or fiber amplifier includes a silica based fiber doped with at least one dopant selected from: Sm, Eu, Dy, Pr.

40. The laser system according to claim 39, wherein said fiber laser or fiber amplifier is pumped by a light source providing a pump wavelength in 375nm to 475 ran range.

41. The laser system of claim 39 wherein said fiber laser or fiber amplifier is pumped by at least one blue broad area laser.
FIG. 1

FIG. 2


**FIG. 10**

1. **Raman wavelength converter I**
   - 106
   - 100W
   - 1169 nm, 50 W
   - 110A
   - 584.5 nm, 30 W
   - 389.7 nm, 12 W
   - 110B
   - 110C
   - 584.5 and 389.7 nm out
   - 110D
   - 233.8 nm, 6 W
   - 1106nm, 50W
   - 102
   - 102'
   - 105
   - 105_1
   - 105_2
   - 106
   - 106_2

**FIG. 11**

1. **Raman wavelength converter I**
   - 106
   - 1158 nm
   - 110A
   - 110B
   - 110C
   - 579 and 386 nm out
   - 231.6 nm

2. **Yb-doped power amplifier I**
   - 105
   - 4W
   - 4W
   - 106
   - 106_2

3. **Yb-doped preamplifier**
   - 102
   - 102'

4. **1041 nm seed pulse generator**
   - 102

5. **193 nm 4 W output**