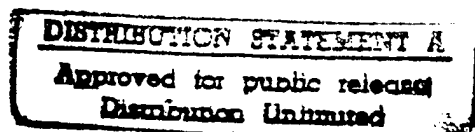


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DTIC QUALITY INSPECTED 2

1 RED LIGHT SOURCE

2
3 SPECIFICATION

4
5 Background of the Invention

6
7 1. Field of the Invention

8 The present invention relates to light sources and
9 particularly to a narrow band, high power and coherent source of
10 light in the red (600-650 nm) spectral region.

11 2. Background of the Invention

12 Photodynamic therapy (PDT) is a promising technique for
13 location-specific treatment of cancerous tumors. Its advantages
14 are that the process is localized to the tumor tissue so that
15 relatively little damage occurs to the surrounding healthy
16 tissue, and the procedure can be frequently done without surgery.
17 The PDT technique begins with the administration of a sensitizer
18 drug, known as a photosensitizer either topically, locally or
19 systematically to the patient, followed by the irradiation of the
20 lesion by light which causes selective damage to the tumor
21 tissue. One frequently used photosensitizer is photofrin, which
22 is photo activated with light at 630 nm. Because of a narrow
23 absorption band of photofrin, the light must have a spectral
24 bandwidth no wider than approximately 3 nm. In order to achieve

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1 reasonably short treatment times optical powers of greater than 1
2 W cw are required, and powers of 3-10 W are desirable. Typically
3 red light is delivered to the treated area via multimode optical
4 fiber with a diameter of a few hundred micrometers.

5 In dentistry, red light is required for cosmetic bleaching
6 of tooth surfaces. The spectral and power requirements (1 W) are
7 less stringent than in PDT. Similarly, large screen visual
8 displays require red light with approximately 1 W cw power, but
9 with near-diffraction limited beam quality, and broad-band
10 spectrum (typically 1-10 nanometers) for speckle-free projection.

11 At the present time, the only available sources of high
12 power red light are laser diodes or dye lasers pumped by high
13 power argon ion lasers. These systems, however, have serious
14 drawbacks and deficiencies. Although laser diodes operating as
15 short as 630 nm have been demonstrated, they exhibit poor
16 lifetimes and have low output powers. While it might be possible
17 to combine the power of a large number of such diodes through the
18 use of multimode optical fibers, it is difficult to have all of
19 the lasers emit within the narrow 3 nm bandwidth required for
20 efficient photofrin absorption. In addition, the wavelengths of
21 individual diodes can be expected to change with temperature
22 variations and device aging. Similarly, while argon laser pumped

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1 dye lasers can generate the required narrow band powers of
2 several watts, the approach suffers from an extremely low
3 electrical-to-optical power conversion efficiency, leading to
4 highly undesirable requirements of large volume water cooling and
5 high voltage power supply lines. Such laser system is also very
6 complex, requiring skilled personnel to maintain proper
7 operation, and very high cost, in the range of \$200-300 thousand.
8 Another major drawback is that dye lasers require the use of
9 toxic and hazardous dyes and solvents which have limited
10 lifetimes and which present disposal problems.

11 The all-solid-state laser system which is the subject of
12 this invention aims at circumventing all of the deficiencies of
13 red emitting lasers just described. Because of its diode pumped
14 solid state configuration, the disclosed laser system does away
15 with the use of dyes, and achieves several orders of magnitude
16 larger electrical-to-optical conversion efficiency than the argon
17 laser based system, allowing operation with a conventional 120 v
18 power supply, and with minimum cooling. In addition, the
19 disclosed laser system is inherently spectrally narrow and
20 capable of maintaining stable operating wavelength. Because of a
21 single spatial mode output, the new laser system also lends
22 itself well toward power scaling through the use of spatial

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1 multiplexing, where outputs of many lasers can be efficiently
2 coupled into a multimode power delivery fiber. Finally, as will
3 be described below, the disclosed laser system consist of
4 relatively low cost components and is relatively simple to
5 assemble and align, which will result in a substantially lower
6 overall system cost than existing approaches.

7
8 Summary of the Invention

9 It is therefore an object of the invention to provide an
10 improved red light source of light.

11 Another object of the invention is to provide a low cost,
12 compact, narrow band , high power and coherent source of light in
13 the red (600-650 nm) spectral region for applications in
14 photodynamic therapy, optical displays and dental treatment.

15 Another object of the invention is to provide an all-solid -
16 state, laser-diode pumped source of red light.

17 A further object of this invention is to provide a narrow
18 band source of light near 630 nm for photodynamic therapy (PTD)
19 using photofrin photosensitizer.

20 These and other objects of this invention are achieved by
21 providing a red light source comprising a first optical source
22 for emitting a first light beam at a first wavelength, a second

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1 optical source for emitting a second light beam at a second
2 wavelength, a combiner for combining the first and second light
3 beams to produce a combined beam, and a nonlinear crystal
4 responsive to the combined beam for producing a sum frequency
5 light beam of red light.

6
7 Brief Description of the Drawings

8 These and other objects, features and advantages of the
9 invention, as well as the invention itself, will become better
10 understood by reference to the following detailed description
11 when considered in connection with the accompanying drawings
12 wherein like reference numerals designate identical or
13 corresponding parts throughout the several views and wherein:

14 Fig. 1 is a schematic diagram of the red light source of the
15 invention;

16 Fig. 2(a) shows a double cladding fiber and v-groove pump
17 coupling arrangement which can be used to construct a high power
18 amplifier either at near 1 micron or at 1.5 microns;

19 Fig. 2(b) illustrates a configuration of a single-
20 polarization fiber amplifier;

21 Fig. 2(c) illustrates a configuration of a single-
22 polarizarion fiber laser;

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1 Fig. 3 shows the quasi-phase-matched (QPM) period and sum
2 frequency wavelength for mixing 1.5 micron emission with 1.064
3 micron Nd:YAG output;

4 Fig. 4 shows a first alternative embodiment of a red light
5 source using a Nd:YAG laser;

6 Fig. 5 shows a second alternative embodiment of a red light
7 source using a Nd:YAG laser and an intracavity nonlinear crystal
8 placement; and

9 Fig. 6 shows a third alternative embodiment of a red light
10 source using a Nd:YAG laser or a Nd- or Yb-doped fiber
11 laser/amplifier for the Yb/Er-doped 1.5 micron fiber amplifier.
12

13 Detailed Description of the Preferred Embodiments

14 In this invention, red light is generated through the
15 process of nonlinear frequency mixing of light at approximately
16 1.0 μm with that at approximately 1.5 μm .

17 Referring now to the drawings, Fig. 1 illustrates a first
18 embodiment of the red light source of the invention. The red
19 light source of Fig. 1 requires two different optical sources,
20 with one being a 1-micron laser or amplifier source 11 for
21 emitting a light beam at a wavelength of about 1-micron and the
22 other being a laser or amplifier source 13 for emitting a light

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1 beam at a wavelength of about 1.5-microns.

2 In operation, the 1-micron and 1.5-micron beams from the
3 sources 11 and 13 are combined in a dichroic beam combiner 15 to
4 spatially overlap the beams. The combined beams are then focused
5 by a lens 17 into a nonlinear crystal 19 to cause the crystal 19
6 to generate an emission in the red spectral band by sum frequency
7 mixing of the two infrared input beams. This red light has a
8 wavelength of about 0.6 microns. An infrared (IR) beam block 21

9 may be placed at the output of the nonlinear crystal 19 to
10 reflect or absorb the remnant infrared 1-micron and 1.5 micron
11 beams and only allow the 0.6-micron, sum frequency red light to
12 be outputted from the red light source of Fig. 1.

13 High efficiency, compactness, low cost, and narrow band
14 operation, required of a practical photodynamic therapy (PDT)
15 laser source, are achieved through the use of a unique
16 combination of components in each of the system diagram blocks of
17 Fig. 1. These components and the overall system operation will
18 now be described.

19 20 OPTICAL SOURCES

21 Laser sources which generate the 1.0 micron (μm) and 1.5
22 micron (μm) beams have to meet several criteria: high electrical

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1 to optical conversion efficiency, compact construction, low
2 component costs, narrow band operation, and linear polarization
3 output. The last condition is imposed by the nonlinear sum
4 frequency generation which requires that for efficient wavelength
5 conversion, the two inputs to the nonlinear crystal are linearly
6 polarized. An optical source which meets the above requirements
7 is a laser diode-pumped fiber amplifier, configured as shown in
8 Fig. 2(a). Fig. 2(a) shows a double cladding fiber and v-groove
9 pump coupling arrangement.

10 More specifically, Fig. 2(a) shows a double cladding fiber
11 23 with an embedded v-groove 25 in the fiber 25 and an exemplary
12 pump, broad stripe, laser diode 27 in a pump-coupling arrangement
13 which can be used to construct a high power amplifier either at
14 near 1 micron (for amplifier 11) or at 1.5 microns (for amplifier
15 13). The laser consists of a double cladding optical fiber 23
16 (crosssection shown), with a single mode core 29 containing an
17 appropriate active dopant (not shown), and a large inner cladding
18 31 which is surrounded by a low refractive index outer cladding
19 33. Double cladding optical fibers are well known in the art.
20 The different wavelengths of 1 micron and 1.5 microns can be
21 generated by putting a selected one of different dopants into the
22 core 29 of this fiber 23. The inner cladding 31 serves to guide

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1 and confine the light from the pump laser diode 27 which is
2 gradually absorbed by the active dopant contained in the fiber
3 core 29. To facilitate coupling of pump light generated by the
4 high power, broad area laser diode (or diodes) 27 into the inner
5 cladding 31, the cladding diameter is made typically 100-300 μm
6 in diameter, comparable to the laser diode emitter width. The
7 outer cladding 33 refractive index is sufficiently low to achieve
8 a high maximum acceptance angle in the inner cladding 31
9 waveguide, to allow efficient capture of highly divergent light
10 from the laser diode 27. In addition, the inner cladding 31
11 shape is typically made to be near-rectangular to prevent helical
12 ray propagation and therefore assure nearly complete absorption
13 of the pump light by the doped core 29.

14 In order to leave the fiber ends unobstructed, the pump
15 light from the laser diode 27 is side-coupled into the inner
16 cladding 31 through the use of the imbedded v-groove 25. Pump
17 light incident on the facet 25A of the v-groove 25 is reflected,
18 by total internal reflection or through the use of a high
19 reflectivity coating (not shown) on the facet 25A, and directed
20 along the fiber 23 axis. Multiple v-grooves 25 and pump laser
21 diodes 27 can be used to increase the total pump power coupled
22 into the fiber 23.

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1 Absorption of the pump light by the active dopant in the
2 core 29 induces optical gain for light propagating in the single
3 mode core 29, so that the fiber 23 constitutes an optical
4 amplifier for light injected into the core 29. With appropriate
5 feedback at each fiber 23 end (not shown), the fiber 23 can
6 support laser oscillation, and single spatial mode emission is
7 generated from the output end of the fiber 23. Since a single
8 mode fiber 23 permits propagation of light with any polarization
9 state, special means must be taken to achieve linearly polarized
10 laser output. This is due to the fact that one of the
11 requirements for generating a sum frequency output in Fig. 1 is
12 that both the 1 micron radiation from source 11 and the 1.5
13 micron radiation from source 13 should be linearly polarized. A
14 technique for constructing a single polarization fiber amplifier
15 is shown in the double pass fiber amplifier arrangement of Fig.
16 2(b).

17 The technique shown in Fig. 2(b) uses a Faraday mirror 35
18 and requires double pass propagation of light through gain fiber
19 37. The fiber could be of the double cladding type shown in Fig.
20 2(a). Linearly polarized input light 39 from a low power seed
21 laser 41, such as a laser diode, passes through a Faraday
22 isolator 43 and is injected into the fiber 37 through a

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1 polarizing beam splitter 45. This linearly polarized input light
2 39 propagates in a first pass through the gain fiber 37,
3 undergoing a change in the polarization state. After reflection
4 from the Faraday mirror 35 and a second pass through the fiber
5 37, the polarization of the light propagating through the fiber
6 37 returns to a linear state but is oriented perpendicular to the
7 polarization of the input light 39. The polarizing beam splitter
8 45 reflects the orthogonally polarized output beam 47, spatially
9 decoupling it from the input beam 39. This arrangement
10 constitutes a single polarization fiber amplifier which is seeded
11 with a narrow-band linearly polarized input light 39 to generate
12 high power linearly polarized output light 47. The Faraday
13 isolator 43 is placed between the seed laser 41 and the gain
14 fiber 37 to assure frequency-stable seed laser 41 operation.

15 Referring now to Fig. 2(c), a double pass fiber laser
16 arrangement is shown. To convert the double pass fiber amplifier
17 arrangement of Fig. 2(b) into the double pass fiber laser
18 arrangement of Fig. 2(c), optical feedback (in the form of a
19 reflective element) is added at the input and output end, as
20 shown in Fig. 2(c). The seed laser 41 and Faraday isolator 43 of
21 Fig. 2(b) are not used in the double pass fiber laser arrangement
22 of Fig. 2(c). In order to achieve narrow-band spectral output, a

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1 frequency selective reflective element 51, such as a diffraction
2 grating is used at the input of the polarizing beam splitter 45.
3 The Faraday mirror 35 provides the second reflective element for
4 the arrangement of Fig. 2(c). Alternately, a fiber with a built-
5 in Bragg grating can be used as one of the feedback elements.
6 The gain fiber could be of the double cladding type shown in
7 Fig. 2(a).

8 Optical gain in the doped fiber core 29 occurs in a spectral
9 range defined by the specific dopant and the pump wavelength.
10 For generation of emission near 1.0 micron (μm) Yb (Ytterbium) is
11 typically used, requiring a pump wavelength of 915 nm
12 (nanometers) or 980 nm. Ytterbium exhibits optical gain in the
13 spectral region of approximately 1020-1150 nm. Another useful
14 dopant in this spectral band is Nd (Neodymium), which requires
15 pumping at 810 nm. Typical dopant concentrations are in the
16 1-2% by weight range. Up to 10 watts (W) of cw (continuous wave)
17 power at 1.0 micron has been generated using Nd or Yb doped fiber
18 lasers. To generate high power emission near 1.5 microns, a
19 fiber co-doped with Yb and Er (Erbium) is used. Although Er
20 alone is commonly used to achieve optical gain in fiber
21 amplifiers used in fiber communication systems, the use of a high
22 concentration (typically 0.1 to 5% by weight, and preferably

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1 about 1%) of the Yb co-dopant allows rapid absorption of a 980
2 micron pump light. The Er concentration is typically in the
3 0.05% to 0.3% range. This rapid absorption is required to
4 compensate for the small ratio (typically about 1:500) of the
5 single mode core 29 to the inner cladding 31, which reduces the
6 effective absorption length for the pump light in a double
7 cladding fiber structure 23. After absorption of 980 micron pump
8 light, the Yb atoms which are excited to an upper energy level
9 transfer their energy to neighboring Er atoms, resulting in
10 optical gain and stimulated emission in the 1520-1550 nm spectral
11 band. Up to 4 W of cw power has been generated at 1.5 microns
12 using Yb/Er doped fibers.

14 SUM FREQUENCY GENERATION AND NONLINEAR CRYSTAL 19

15 As mentioned before in the discussion of Fig. 1, to generate
16 red light near 0.6 microns, the two (infrared) 1.0 and 1.5 micron
17 beams from sources 11 and 13 are spatially superimposed by a
18 dichroic beam combiner 15 and are focused by lens 17 into the
19 nonlinear crystal 19. The nonlinear crystal generates a sum
20 frequency emission at a wavelength λ_s :

$$21 \quad \lambda_s = \lambda_1 \lambda_2 / \lambda_1 + \lambda_2 \quad (1)$$

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1 where λ_1 and λ_2 are the wavelengths of the incident beams. For
2 $\lambda_1 = 1064$ nm, corresponding to the peak of Nd doped fiber or
3 Nd:YAG laser emission, and $\lambda_2 = 1535$ nm, corresponding to the peak
4 emission wavelength of Yb/Er doped fiber amplifier or laser, the
5 sum frequency wavelength is $\lambda_3 = 628.5$ nm.

6 One of the key components of the disclosed invention is the
7 nonlinear crystal 19 used to perform sum frequency generation.
8 The crystal 19 must meet several requirements: i) low cost and
9 availability in large sizes, ii) low absorption at the incident
10 beam and the sum frequency wavelengths, iii) phase matched
11 operation for sum frequency generation at wavelengths of
12 interest, iv) high nonlinear coefficient, v) small or zero walk-
13 off angle. The last three conditions are required in order to
14 achieve high sum frequency conversion efficiency for available
15 incident pump powers.

16 A crystal 19 which meets all of the above conditions is
17 quasi-phase-matched (QPM) LiNbO_3 or LiTaO_3 , fabricated by a
18 process of periodic field poling. Such a crystal 19 offers the
19 advantages of non critical phase matching, resulting in a zero
20 walk-off angle and a large angle tolerance for the crystal 19
21 positioning angle, good transparency for the wavelengths of
22 interest, and most importantly, very high nonlinear coefficient.

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1 In addition the (QPM) LiNbO_3 crystal, through a proper choice of
2 domain period Λ can be engineered for any specific combination of
3 interacting wavelengths. The phase matching condition in a QPM
4 crystal is satisfied when:

5
6
$$n_3/\lambda_3 - n_1/\lambda_1 - n_2/\lambda_2 = 1/\Lambda \quad (2)$$

7

8 where n_1, n_2, n_3 is the refractive index at $\lambda_1, \lambda_2, \lambda_3$.

9 Fig. 3 shows the quasi-phase-matched (QPM) period and sum
10 frequency wavelength for mixing 1.5 micron emission with 1.064
11 micron Nd:YAG output emission. More specifically, Fig. 3 shows
12 the required QPM period for performing phase matched sum
13 frequency generation of input wavelengths of $\lambda_1 = 1064$ nm, with λ_2
14 varying from 1530 nm to 1565 nm, corresponding to the high gain
15 range of a Yb/Er fiber amplifier. The resulting sum frequency
16 wavelength, varying from 627 nm to 635 nm, is also shown. The
17 required QPM domain periods is approximately 11 microns, well
18 within the range of domain periods which have been demonstrated.
19 Since the operating range of a Yb-doped fiber amplifier is
20 approximately 1020-1150 nm, and that of an Er-doped amplifier is
21 1530-1565 nm, the spectral range of sum frequency light which can
22 be generated is 617-656 nm, corresponding to the nearly entire

1 red region of the visible spectrum.

2 One of the important considerations in the disclosed laser
3 configuration of Fig. 2(c) is the optical efficiency of the sum
4 frequency conversion process. Sum frequency power P_3 is given as
5 a function of the incident powers P_1 and P_2 by:

6
7
$$P_3 \cong [(8\omega_0^3 d^2) / (\pi n_1 n_2 n_3 \epsilon_0 c^4)] \times (h L P_1 P_2) \quad (3)$$

8

9 where pump depletion is neglected, $\omega_0 = (\omega_1 + \omega_2) / 2$ is the mean
10 frequency of the input beams, d is the effective nonlinear
11 coefficient, h is a focusing parameter which equals 1.07 for
12 optimum focusing, and ϵ_0 is the free space dielectric constant.
13 The nonlinear constant of QPM LiNbO₃ is given by $2d_0/\pi = 17$ pm/v,
14 where $d_0 = 27$ pm/v is the nonlinear coefficient of bulk LiNbO₃.
15 For the case of $P_1 = 1$ W, $P_2 = 1$ W and a $L = 1.0$ cm long crystal, the
16 above equation predicts $P_3 = 0.06$ W. For a longer crystal of 5 cm
17 and higher pump powers of $P_1 = 2$ W, $P_2 = 2$ W, a sum frequency
18 power of 1.2 W is calculated. Although the actual sum frequency
19 power is expected to be somewhat smaller because of significant
20 pump depletion, this results shows that multi-watt output powers

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1 near 630 nm are feasible with reasonable crystal lengths and
2 infrared pump powers.

3 For the case of low average output power of the fiber
4 sources, large conversion efficiency can still be achieved if the
5 amplifiers are operated in pulsed mode. Pulsed output can be
6 easily achieved in the case of the optical amplifier
7 configuration of Fig. 2(b), by operating the seed laser 41 (Fig.
8 2(b) in a pulsed mode. When seeded with short pulses with a
9 risetime of a few nanoseconds (well within direct current
10 modulation capability of laser diodes) the peak power level P_p of
11 the amplified pulses generated by the fiber amplifier (of Fig.
12 2(b)) are given by $P_p = G_s P_i$, where P_i is the seed power, and G_s
13 is the small signal gain of the amplifier. For a typical fiber
14 amplifier, small signal gain 30 dB, a seed power of only 100 mW
15 is required to produce an output pulse with a 100 W peak power.
16 For a pulse repetition period which is much shorter than the
17 excited state lifetime (10 ms [milliseconds] for Er and 0.5 ms
18 for Nd) of the active dopant, the output power can be maintained
19 close to that which would occur under cw operation. To assure
20 temporal coincidence between the pulses generated by the 1.0
21 micron fiber amplifier and the 1.5 micron amplifier, the two seed
22 laser diodes can be driven by a single pulse generator. From the

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1 above discussion of sum frequency conversion efficiency, it is
2 clear that such high peak powers would produce efficient
3 conversion of the infrared pump power into red emission.
4

5 ALTERNATIVE CONFIGURATIONS

6 Several alternative embodiments for the red light source are
7 shown in Figs. 4, 5 and 6.
8

9 In Fig. 4, a lamp or diode-pumped Nd:YAG laser 53 is used
10 to provide high power pump light at 1.06 μm . Such lasers are
11 commercially available and generate high power (over 10 W) of cw
12 emission at 1.06 nm with narrow spectrum.

13 In the operation of the embodiment of Fig. 4 the pump lasers
14 are comprised of a 1.064 micron Nd:YAG laser 53 and a 1.5 micron
15 fiber laser or amplifier 55. The outputs of these two sources 53
16 and 55 are combined with a dichroic beam combiner 57 which
17 reflects light at 1.5 microns and transmits light at 1.064
18 microns. After the 1.064 and 1.5 micron beams are combined by
19 the combiner 57, the combined beams are focused by a lens 59 into
20 a nonlinear crystal 61. The nonlinear crystal 61 is responsive
21 to the combined beams for generating the sum frequency red light
22 at a wavelength of about 0.6 microns. In the path of the beam

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1 there is an IR (infrared) beam block 63 which absorbs or reflects
2 the 1.064 and 1.5 micron infrared beams and only allows the red
3 light at about 0.6 microns to pass therethrough as output light.

4 If the source 55 is a 1.5 micron laser, it would look like
5 the laser shown in Fig. 2(c). On the other hand, if the source
6 55 is a 1.5 micron amplifier, it would look like the amplifier
7 shown in Fig. 2(b) and contain the seed laser 41 in it. As
8 mentioned before the seed laser 41 in Fig. 2(b) could be a laser
9 diode. Although such a laser diode would generate a weak signal,
10 that weak signal would be amplified in the amplifier of Fig.
11 2(b).

12
13 Another embodiment of a red source is shown in Fig. 5 which
14 is different from the embodiments shown in Figs. 1 and 4. The
15 embodiment of Fig. 5 uses intracavity sum frequency generation,
16 where the nonlinear crystal 67 is placed inside a resonant cavity
17 69 of a Nd:YAG laser 71. More specifically, the nonlinear crystal
18 67 is placed between the two dichroic laser end mirrors 71 and 73
19 of the cavity 69. The dichroic laser mirror 71 is coated to be
20 highly reflective (HR) at 1.06 microns and anti-reflective (AR)
21 at 1.5 microns. On the other hand, the dichroic laser mirror 73
22 is coated to be highly reflective at 1.06 microns and anti-

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1 reflective at 0.63 microns to allow 0.6 micron red light to be
2 transmitted out of the cavity 69. The gain medium of the laser
3 65 is a Nd:YAG crystal 75 which is placed between the
4 nonlinear crystal 67 and one of the end laser mirrors such as the
5 mirror 71.

6 In the operation of the embodiment of Fig. 5, light from a
7 1.5 micron fiber laser (Fig. 2(c)) or amplifier (Fig. 2(b)) is
8 incident on a Nd:YAG laser and passes through the dichroic laser
9 mirror 71.

10 So in the embodiment of Fig. 5 the sum frequency light is
11 generated inside of the cavity 69 of this Nd:YAG laser by mixing
12 the 1.5 micron light which is incident from the source 75 and
13 mixing it in the nonlinear crystal 67 with the intracavity 1.06
14 micron light from the Nd:YAG laser. It is the nonlinear crystal
15 67 which does the sum frequency mixing to produce the 0.6 micron
16 red light which is transmitted out of the cavity 69 by way of the
17 dichroic laser mirror 73.

18 The advantage of the placement of the nonlinear crystal 67
19 in an intracavity position inside the Nd:YAG laser 65 is that the
20 circulating power inside the laser cavity 69 is approximately one
21 hundred times larger than the output power outside the cavity 69.
22 When a 1.5 micron pump beam from a laser/amplifier 75 is focused

1 by a lens 77 into the laser cavity 69 through the dichroic cavity
2 mirror 71, this results in a much higher sum frequency mixing
3 efficiency than the possible crystal 67 placement outside the
4 cavity 69. The red sum frequency signal is generated
5 unidirectional to the right of the nonlinear crystal 67 and is
6 coupled out of the laser cavity through the dichroic cavity
7 mirror 73 which is transparent near 630 nm.

8
9 Another embodiment of a red source is shown in Fig. 6.
10 In Fig. 6, a light source 81 operates to generate light at 1.06
11 microns. The light source 81 can either be a 1.064 micron Nd:YAG
12 laser or a Nd (Neodymium) or Yb (Ytterbium) -doped fiber laser
13 amplifier. This fiber laser or amplifier could take the form of
14 the amplifier of Fig. 2(b) or the laser of Fig. 2(c), depending
15 on what the fiber is doped with. If the fiber is doped with Nd or
16 Yb, it generates light at near 1.06 microns. (If the fiber is
17 doped with Er (erbium) or Er/Yb, it can generate light at near
18 1.5 microns.)

19 For purposes of this description, the light source 81 emits
20 light at 1.06 microns. Then the light emerging from this 1.06
21 micron source 81 is split into two parts by a beam splitter 83.
22 One part is directed down, reflected by a mirror 85, goes through

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1 a dichroic beam combiner 87 and is then focused by a lens 89 into
2 a nonlinear crystal. The other part of the 1.06 micron beam that
3 was generated by the Nd or Yb doped laser or amplifier of the
4 light source 81 passes through the beam splitter 83, a fiber
5 Bragg grating 93 having high reflectivity at 1.5 microns, and a
6 polarizing beam splitter and serves to pump an Yb/Er
7 (Ytterbium/Erbium) -doped single mode fiber laser 97. The laser
8 cavity 99 of the laser 97 is similar to that shown in Fig, 2(c),
9 with the exception that this cavity 99 is shown being pumped by
10 the 1.06 micron laser beam from the light source 81.

11 The cavity 99 is formed between the fiber Bragg grating 93,
12 which is highly reflective at 1.5 microns, and a partial mirror
13 101 which is represented by a dashed line. The fiber Bragg
14 grating 93, which passes the 1.06 micron beam, constitutes one of
15 the mirrors of the cavity 99. The partial mirror 101 operates as
16 the second mirror of the cavity 99.

17 In operation the laser 97 is pumped by the 1.06 micron beam.
18 As a result, the 1.06 micron enters the fiber laser 97, is
19 absorbed by the dopants, by the Yb. This absorption of the 1.06
20 micron light by the dopants causes a population inversion of the
21 Er atoms which then produces a gain at 1.55 microns. So the
22 output of this fiber laser 97 is at 1.5 microns. This 1.5 micron

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1 output passes through the partial mirror 101 and is incident on
2 the dichroic beam combiner 87. The combiner 87 then reflects the
3 1.5 micron beam and combines it with the 1.06 micron beam. Then
4 the combined 1.5 and 1.06 micron beams are both incident on the
5 nonlinear crystal 91, causing the nonlinear crystal 91 to perform
6 the sum frequency generation to generate red light at about 0.6
7 microns. The red light is separated by an IR beam block 103 from
8 the remnant infrared beams at 1.06 and 1.5 microns before being
9 outputted as a 0.6 micron sum frequency output. So after the IR
10 beam block 103 only the red light is emitted, with remnant
11 infrared 1.06 and 1.5 micron beams being reflected back or
12 absorbed by the IR beam block 103.

13
14 ADVANTAGES AND NEW FEATURES OF THE INVENTION
15

16 The red light source of the invention offers the following
17 advantages and features which are not otherwise available in
18 other laser sources operating in the red spectral region: i) all
19 solid state construction, ii) compact configuration and efficient
20 electrical to optical power conversion, iii) wide choice of
21 generated wavelengths in the red 617-656 nm range, iv) narrow
22 band emission, v) pulsed operation with flexible pulse length

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1 and duty cycle characteristics vi) low fabrication costs, and
2 long operating lifetime (based on long lifetimes of pump laser
3 diodes), vii) requires no consumable materials such as dyes,
4 solvents or gases, viii) the output beam is diffraction limited.

5 6 ALTERNATIVES

7 Alternatives to the disclosed red light source are a HeNe
8 gas laser, dye lasers pumped by an Ar ion gas laser, and fiber
9 coupled laser diodes emitting in the red. A HeNe laser emits at
10 632.8 nm and typically generates maximum powers of only 100 mW,
11 insufficient for the photodynamic therapy application. Dye
12 lasers, as discussed above, suffer from poor efficiency, very
13 high cost, and the requirement for frequent dye and solvent
14 replacements. Although laser diodes emitting in the red spectral
15 range have been demonstrated, and it is possible, through the use
16 of multimode optical fibers, to couple many laser diodes in order
17 to generate the required multi-watt power levels, this approach
18 suffers from two major difficulties. The first is that currently
19 laser diodes operating near 630 nm suffer from poor operating
20 lifetime, and the second is that since each diode operates at a
21 slightly different wavelength, it is unlikely that a large number
22 of laser diodes will emit within the required 3 nm bandwidth. In

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1 addition, laser diode based system would produce a multi-spatial-
2 mode output which leads to a lower achievable power density and
3 is unattractive for applications in optical displays.
4

5 Therefore, what has been described is a red light source
6 comprising a first optical source for emitting a first light beam
7 at a first wavelength, a second optical source for emitting a
8 second light beam at a second wavelength, a combiner for
9 combining the first and second light beams to produce a combined
10 beam, and a nonlinear crystal responsive to the combined beam for
11 producing a sum frequency light beam of red light.
12

13 It should therefore readily be understood that many
14 modifications and variations of the present invention are
15 possible. It is

16 therefore to be understood that

17 the invention may be practiced otherwise than as
18 specifically described.

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ABSTRACT

A narrow band, high power and coherent source of red light in the red (600-650 nm) spectral region is disclosed. The red light source comprises a first optical source for emitting a first light beam at a first wavelength, a second optical source for emitting a second light beam at a second wavelength, a combiner for combining the first and second light beams to produce a combined beam, and a nonlinear crystal responsive to the combined beam for producing a sum frequency light beam of red light.

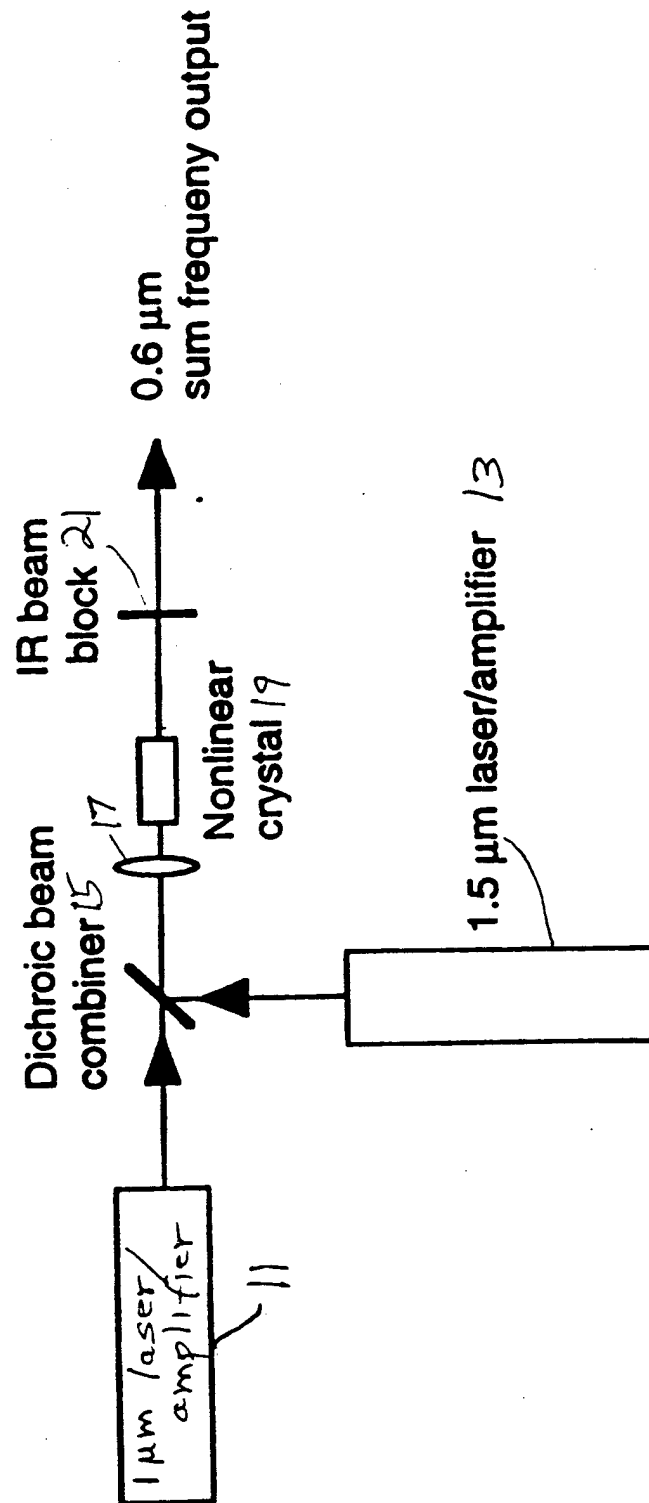


FIG. 1

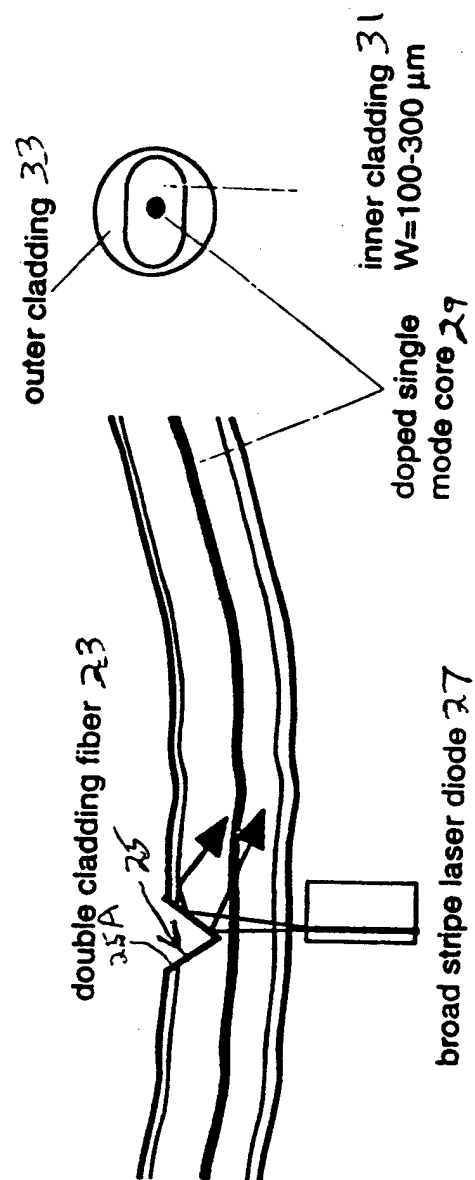


FIG. 2(a)

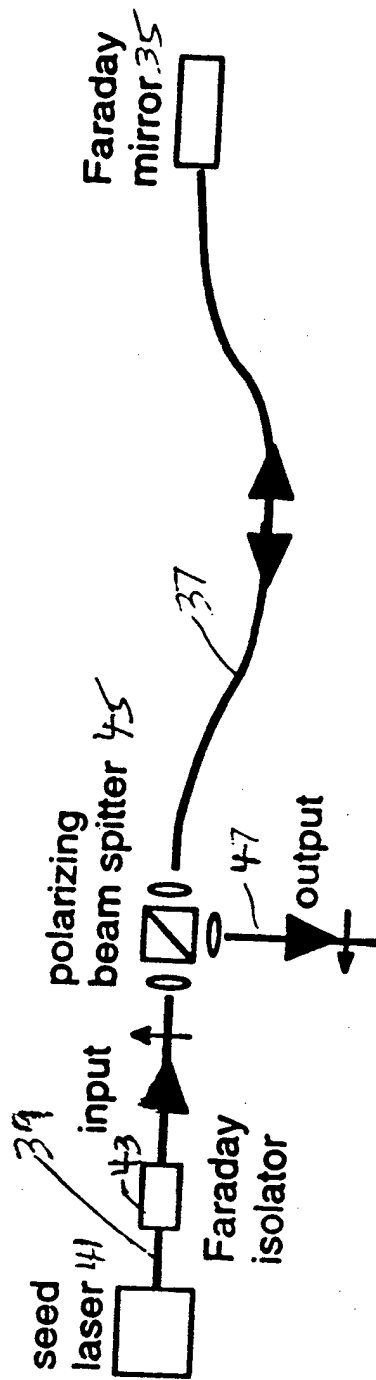


FIG 2(b)

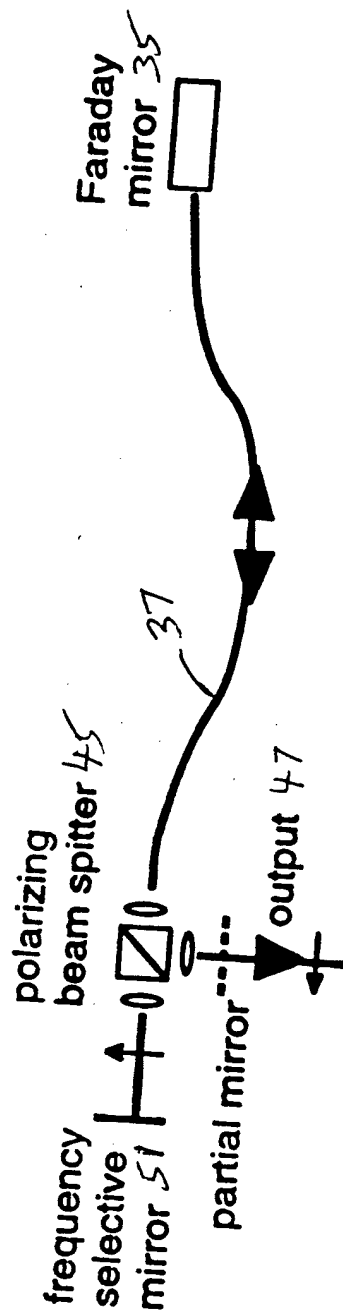


FIG 2(c)

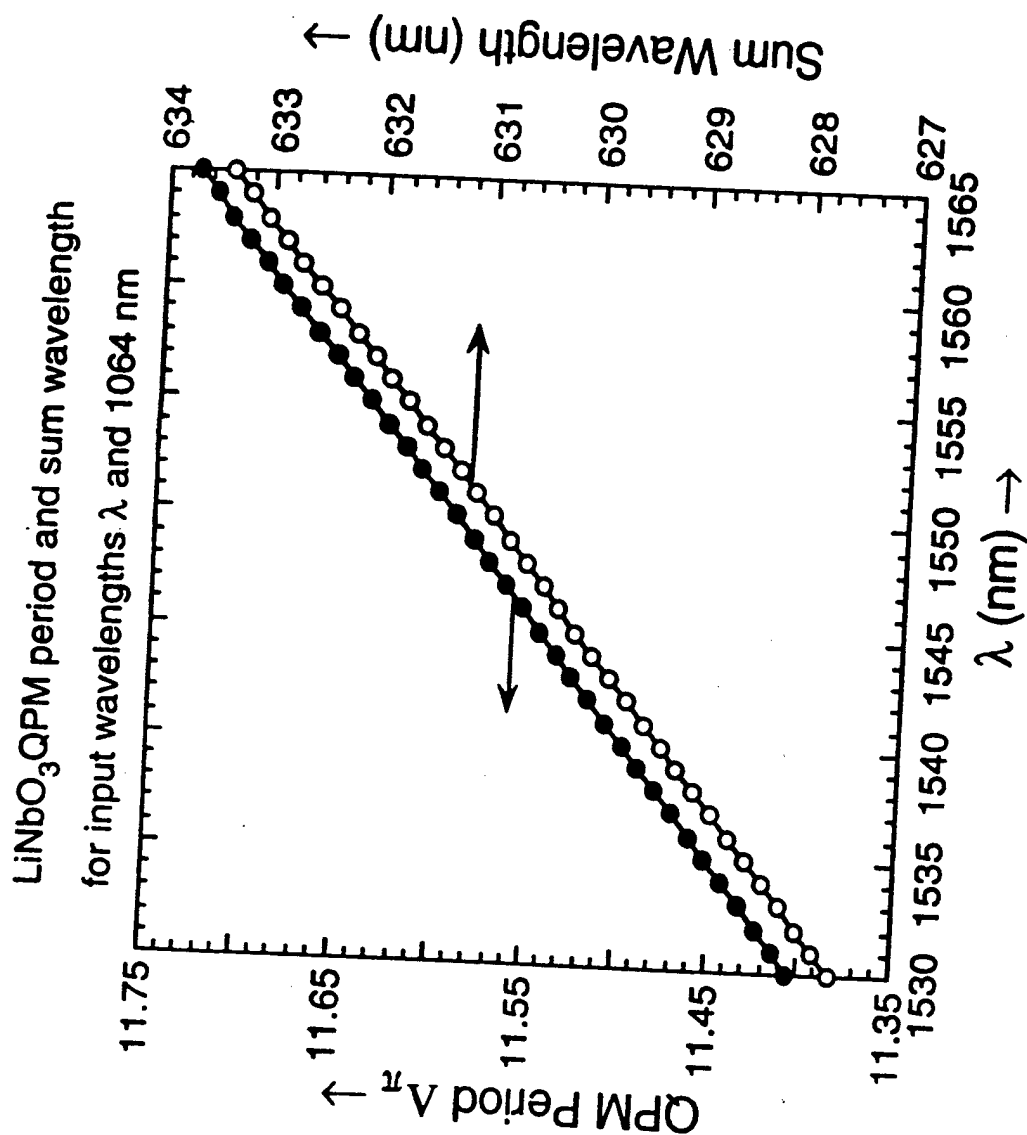


FIG. 3

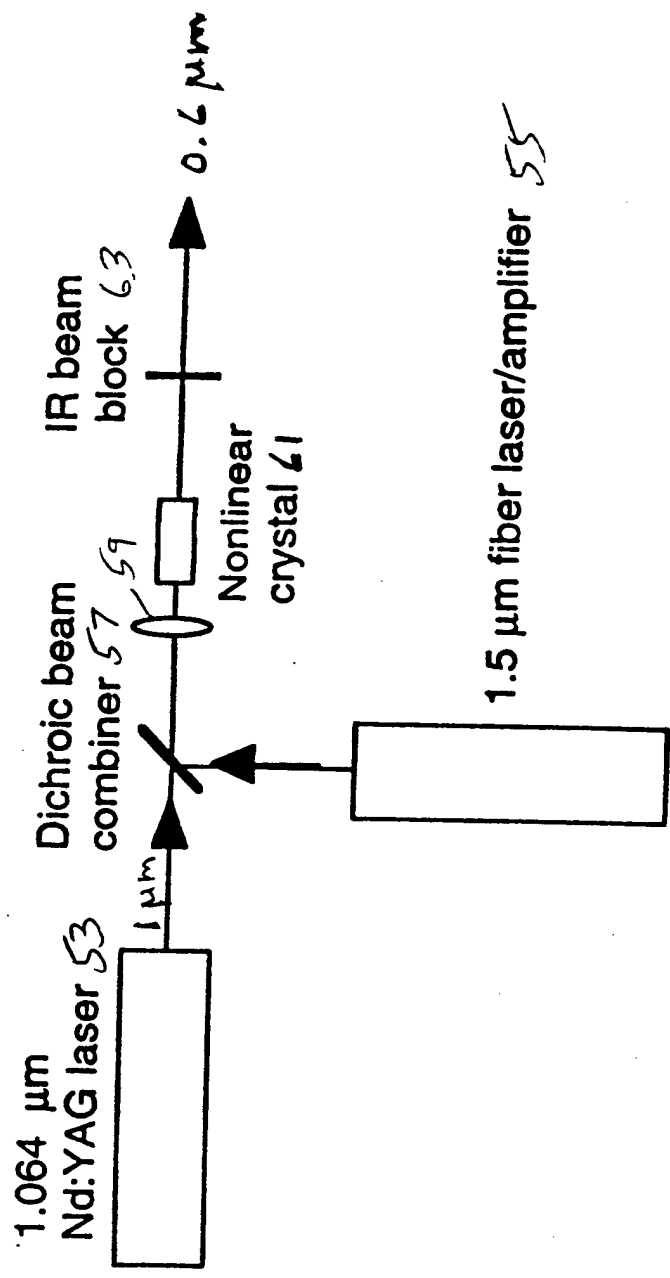


FIG. 4

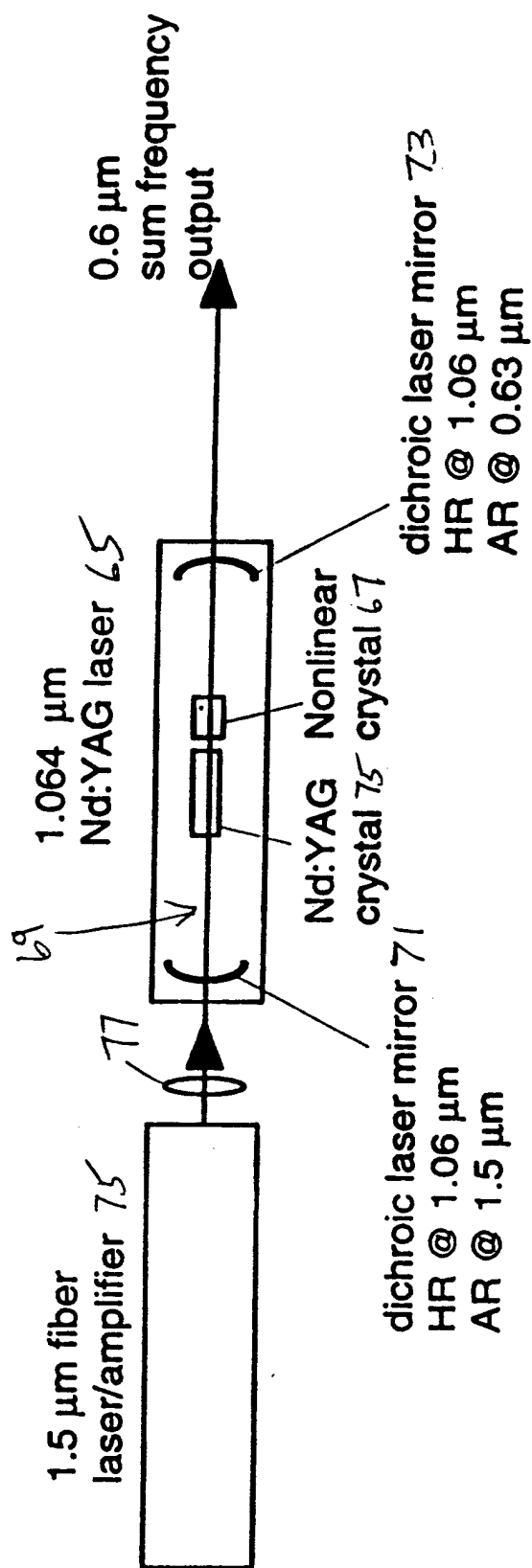


FIG. 5