

1.5 micron imaging source and imaging device incorporating the source

The field of the invention is that of imaging systems for locating targets in a given environment, the target possibly being airborne or ground-based, and notably active imaging enabling automatic control of a laser
5 aiming system from said imaging system.

Generally, active imaging uses its own light source, conventionally a pulsed laser. By virtue of the directivity of the emission and the energies involved, a signal is received over a large distance even through a scattering medium. These characteristics have in particular given this technology a
10 significant importance for security and defense. The photons emitted by a laser and reflected by various objects in a theatre are collected by a receiver-imager. The joint use of a pulsed laser and a time window on reception allows a section of space containing the targets of interest to be selected.

The field of interest is notably the aiming of directed optical-energy
15 weapons requiring correction of effects due to atmospheric turbulence on the free propagation of laser beams. This correction entails measuring the position of the target with a high spatial angular resolution of about 1 microradian with a bandwidth of about 500 Hz, ensuring the first level of compensation of the deformation of the wave surface. Moreover, the
20 illumination system must operate at a wavelength close to that of the weapon.

For example, an active imager, operating at 1.5 μm for eye safety reasons, may be composed of an illuminating laser delivering energy of about 250 millijoules per pulse, the duration of which is about
25 500 nanoseconds, and an imager (camera) having an open time window of the order of a microsecond (so as to reduce the effects due to solar backscattering) with a spectral filter width of about ten nanometers. This architecture is a structure designed to satisfy the range and size criteria for the objects to be processed.

30 In this context, the problem is therefore the availability of such a light source emitting in a spectral region close to 1.5 μm in a wavelength spectral window of $\Delta\lambda = \pm 2 \text{ nm}$ (also for eye safety) and delivering an energy per pulse of 250 mJ at a rate of 1 kHz. This source must moreover be coupled to

an optical device (zoom) that adjusts the illuminated field to the target and to the illuminating distance, the field of observation possibly vary from 1.5 mrad to 5 mrad.

Currently, no solution has been demonstrated that meets all of the
 5 desired specifications. High-energy illumination sources have been developed for long-distance airborne applications requiring a low repetition frequency operating mode (video frequency being sufficient).

The commonest solution consists in converting, in frequency, a solid-state laser (neodymium ion Nd^{3+} -doped glass or crystal) operating in a pulsed
 10 mode near 1 μm . The frequency conversion at around 1.5 μm is produced by way of a nonlinear interaction with an optical parametric oscillator (OPO) formed from a nonlinear crystal, for example KTiPO_4 (KTP) or KTiAsO_4 (KTA) inserted into a cavity resonant at 1.5 μm . A few publications report sources of this type with an energy greater than 100 mJ but at limited repetition rates of
 15 less than 30 Hz, as described in the following articles: "Efficient, high-energy, KTP OPO pumped with 1 μm Nd-lasers" G.A. Rines *et al.*, OSA Proceedings on Advanced Solid State Lasers (1994). "150mJ 1550nm KTA OPO with good beam quality and high efficiency" D.J. Armstrong *et al.*, SPIE Vol. 5337, Conference: nonlinear frequency generation and conversion materials (2004).
 20 "Novel, efficient, high brightness KTP OPO-OPA in single beamline" J.C. McCarthy *et al.*, OSA Proceedings on Advanced Solid State Lasers (2001).

An operation at much higher rates, of the order of a kilohertz, and with an energy level consistent with the signal wavelength, has never been reported and would be very problematic due to the residual absorption of the
 25 usual nonlinear crystals and especially their poor thermomechanical properties.

Another technological approach consists in using a solid medium doped with the erbium ion (Er^{3+}) that has the particularity of being able to directly emit a laser ray at around 1.5 μm . Unfortunately, the effective stimulated
 30 emission cross section of erbium is small and leads to a very high saturation intensity (10-30 J/cm^2), which causes a few problems due to the optical damage threshold of the components that form the laser cavity. This results in a limited extraction energy (<10%) which does not favor high average-power operation. On the other hand, embodiments exceeding 100 mJ per pulse
 35 published at the present time relate only to erbium-doped glasses for which

the repetition rate is very low, less than 1 Hz because of their very poor therm-opto-mecanical properties, as described in the article "50 mJ/30 ns FTIR Qswitched diode-pumped ErYb:Glass 1.54μm laser" E. Georgiou *et al.*, Opt. Com. 198 (2001) 147-153.

5 The conventional geometry of the active medium (rod-shaped, plate-shaped, etc.) optically pumped transversely is not generally favorable to good heat exchange. Conversely, a fiber amplifier medium having a small diameter and a great length has a much better equivalent heat exchange area. This improved thermal management and the improved yield characteristic of fiber
10 amplifiers and lasers favor this technological approach for generating high average powers at around 1.5 μm. In particular, an erbium/ytterbium-codoped fiber laser emitting approximately 300 W at 1.5 μm continuous-wave has already been demonstrated and described in the article: "Erbium:Ytterbium Codoped Large-Core Fiber Laser with 297 W Continuous-Wave Output
15 Power", Y. Jeong *et al.*, IEEE J. of Selected Topics in Quantum Electronics, Vol. 13, No. 3, 573-579, 2007.

The principal limitation of the fiber architecture is its small active volume that limits the amount of energy that can be extracted. The latter is related to the saturation energy and to the small-signal gain G_0 in the following
20 way:

$$E_{extr} = E_{sat} \ln(G_0) \quad \text{where} \quad E_{sat} = \frac{h\nu_s A}{(\sigma_{es} + \sigma_{as})}$$

with: E_{extr} : the extractable energy and E_{sat} : the saturation energy;
 $h\nu_s$: the energy of the signal photons;

25 σ_{es} and σ_{as} : respectively, the effective emission and absorption cross-sections at the signal wavelength; and

A: the effective interaction area (corresponding to the doped core).

In practice, the maximum energy that can be extracted from a fiber amplifier is about 10 times the saturation energy, for an unsaturated gain of
30 about 40 dB. Beyond this, the amplification of the spontaneous emission is such that it saturates the transition and any additional pumping amplifies this noise.

It is enough, in principle, to increase the diameter of the fiber to extract more energy. However, if it is desired to guarantee a beam quality of

about 20 mm × mrad (i.e. an M coefficient such that $M^2 = 10$), the diameter of the doped core is limited to 100 μm for a realistic numerical aperture of 0.1.

Under these conditions, the extractable energy is limited to about ten millijoules because the factor $\sigma_{es} + \sigma_{as} = 7 \times 10^{-21} \text{ cm}^2$ at $\lambda = 1.56 \text{ μm}$.

5 Figure 1 shows an exemplary numerical simulation of the energy that can be extracted from such a fiber as a function of the pump power at 940 nm for different energy levels injected into the amplifier.

10 In this context, one subject of the present invention is an imaging source emitting at 1.5 microns and capable of delivering an optical beam of sufficient energy and in sufficiently short pulses to produce active imaging and notably to follow the target to be destroyed.

15 More precisely, one subject of the present invention is a pulsed laser imaging source emitting at a wavelength of about 1.5 microns in a spectral band $\Delta\lambda$ of a few nanometers and delivering a power of between at least a few tens of millijoules and several hundred millijoules, characterized in that it comprises:

- a source emitting a wave having pulses of greater than approximately a few tens of nanoseconds duration;
- an amplifier assembly delivering an amplified wave from the wave
- 20 output from the pulse source;
- a set of N fibers connected in parallel, supplied with the amplified wave, each of the fibers connected in parallel being coupled to an output amplifier.

25 According to one variant of the invention, the imaging source comprises a coupler enabling the energy of the amplified wave to be distributed to the inputs of the N fibers.

According to one variant of the invention, the imaging source furthermore comprises an optical system enabling the field of observation to vary from 1 milliradian to several milliradians.

30 According to one variant of the invention, the optical system comprises a set of N coupled optics at the outputs of the N fibers.

According to one variant of the invention, the optical system comprises a set of N fibers recombined into M output fibers by a set of couplers.

According to one variant of the invention, said optics comprise a pair of lenses and means for adjusting the distance between lenses so as to vary the field of observation.

According to one variant of the invention, said optics comprise a pair
5 of prisms and means for rotating said prisms so as to vary the angular position of each prism relative to the other and thereby the field of observation.

According to one variant of the invention, the amplifier assembly comprises a series of several amplifiers for generating from a signal wave of
10 a few tens of nanojoules an amplified wave of energy greater than at least about one hundred millijoules.

According to one variant of the invention, the amplifier assembly comprises three diode-pumped fiber amplifiers.

According to one variant of the invention, the fibers are erbium-doped
15 fibers or erbium/ytterbium-codoped fibers.

According to one variant of the invention, the imaging source comprises 25 fibers connected in parallel so as to generate an optical beam of about 250 millijoules of energy.

Another subject of the invention is an imaging device operating at a
20 wavelength near 1.5 microns comprising an imager, characterized in that it comprises the source of the invention, the imager having an open time window of the order of a microsecond associated with a spectral filter about 10 nm in width

Such an imaging device is particularly well suited to imaging that
25 circumvents solar backscattering phenomena during the analysis of aerial elements and the risk of dazzling by those parts of the target that are heated to a high temperature by the laser weapon.

The invention will be better understood and other advantages will become clear on reading the following nonlimiting description and by virtue of
30 the appended figures among which:

- figure 1 shows an example of numerical simulation of the energy that can be extracted from a fiber optical source according to the prior art as a function of the pumping power at 940 nm and for different energy levels injected into the fiber;

- figure 2 shows an example of an imaging source according to the invention comprising the parallel placement of 25 fibers;
- figure 3 shows a matrix arrangement demonstrating the resulting composite optical beam of the imaging source at 1.5 μm . The circles ch_i denote the fields of observation relating to each of the laser beams;
- figure 4 shows a variant of the invention in which some of the output amplifying fibers are recombined; and
- figure 5 shows an example of the imaging source according to the invention furthermore comprising diasporameter type means used to enlarge the imaging field.

Generally, the imaging source according to the invention comprises at least one source emitting a wave capable of being pulsed. Typically, a diode laser may be used, delivering an amplification chain that itself supplies the set of fibers connected in parallel so as to generate the imaging source.

An example of the solution provided by the invention is shown in figure 2 and it is based on the capacity of laser amplifiers, notably erbium-doped fiber amplifiers, to provide pulses a few hundred nanoseconds wide at a repetition frequency of the order of 1 kHz with an energy level of 10 mJ per pulse, with a beam quality factor M^2 of about 10 and over a spectral band $\Delta\lambda$ of a few nm. The flexibility of the fiber amplifier medium lends itself to the parallel placement of a few tens of amplifiers so as to provide the energy level required for illuminating distant targets. More precisely, in the example shown in figure 2, a signal diode D_s delivers a signal wave with an energy of about 0.01 μJ to a first amplifier Ampli1. A single-core single-mode erbium-doped fiber amplifier may for example be used. The fiber for example has a core diameter from 5 to 10 μm and supports just one mode at 1.5 μm . The fiber is pumped with a pump diode D_{p1} at 980 nm of less than 1 W power and coupled to a single-mode fiber. The fiber doping and length are chosen so as to obtain a gain of 30 dB and an output energy of at least 10 μJ , i.e. an average power of 10 mW at 1 kHz.

The amplified signal wave having an energy of about 10 μJ is injected in turn into a second amplifier Ampli2 pumped by a second pump D_{p2} enabling a amplified signal wave with an energy of about 250 μJ to be obtained. A dual-core Yb:Er-doped fiber amplifier may for example be used. The signal core

has a diameter of at least 20 μm so as to enable an output energy of 250 μJ to be obtained and the numerical aperture may vary from 0.1 to 0.2. The pump core is, for example, 250 μm with a numerical aperture greater than 0.4 making the coupling of the pump easier. The pump is, for example, a diode at
 5 920 – 980 nm of at least 10 W coupled to a fiber of 200 μm core diameter and of 0.22 numerical aperture. The average output power is 0.25 W at a rate of 1 kHz. The fiber length may typically vary from 2 to 10 m depending on the doping levels used and the pump wavelength.

This signal wave continues to be amplified in the amplification chain
 10 with a third amplifier Ampli3 pumped by a third pump diode D_{p3} . A dual-core Yb:Er-doped fiber amplifier may for example be used. The signal core has a diameter of approximately 100 μm enabling the output energy to be greater than 10 mJ. The numerical aperture is about 0.1 to ensure a beam quality of 20 mm.mrad corresponding to an M^2 factor equal to 10. The pump core is for
 15 example 400 μm with a numerical aperture greater than 0.4 making pump coupling easier. The pump is, for example, a diode at 920 – 980 nm with a power of at least 100 W coupled to a fiber of 400 μm core diameter and of 0.22 numerical aperture. The average output power is 10 W at a rate of 1 kHz. The fiber length may typically vary from 2 to 10 m depending on the doping
 20 levels used and the pump wavelength.

Thus, a signal wave of about 10 mJ energy is obtained that may supply, via a coupler C_{pi} a set of fibers F_i , here numbering 25 in the current example. The 10 mJ of energy is distributed as an elementary energy of 250 μJ to each of the 25 fibers. A set of 25 amplifiers comprising pump diodes
 25 D_{Np4} allows each of the fibers F_i to deliver at their outputs an energy of 10 mJ, i.e. a total pulse source energy of 25 x 10 mJ or 250 mJ.

These 25 amplifiers are identical to the amplifier Ampli3. The junction between the amplifiers Ampli1 and Ampli2 then Ampli2 and Ampli3 is produced using taper fibers, the geometry of which varies so as to match the
 30 mode diameter between two amplifying fibers. Between these amplifiers, fiber components such as wavelength filters, acousto-optic modulators or optical isolators may be inserted so as to minimize the amplification of noise between the pulses and to avoid an oscillation.

Moreover, it is also possible to produce the amplifiers Ampli2 and
 35 Ampli3 using similar fibers but doped only with erbium. In this case, the pump

wavelength is preferably at around 978 nm and the length of the fibers must be increased because the absorption is less severe.

The coupling between the amplifier Ampli3 and the 25 amplifiers is produced using a multimode 1×25 coupler. This component may be produced
 5 either using a tree of multimode 1×2 couplers, or using just one component that enables this transition to be obtained.

Thus, according to the invention, the injection of these N parallel amplifiers with a common pilot signal ensures the synchronicity and the temporal format and the wavelength of the emission.

10 So as to produce an imaging source, each of these lasers is associated with an optic the diameter of which is given by:

$$\phi_{optic} = \frac{4M^2 \times \lambda}{\pi\theta}$$

M^2 characterizes the difference between the beam quality relative to its diffraction-limited value (M^2 equal to 1); and

15 λ is the wavelength and θ is the field of observation:

Thus, for $M^2 = 10$ at $\lambda = 1.5 \mu\text{m}$ and for $\theta = 1.5 \text{ mrad}$: $\phi_{optic} = 12.7 \text{ mm}$ is obtained.

The pupil composed of 25 lasers, delivering a total energy of about 250 mJ, may therefore be 65×65 in size.

20 More precisely, each laser beam at the output of each of the 25 fibers is coupled to an lens-type optic, arranged in a matrix as shown in figure 3, that demonstrates the resulting composite optical beam of the imaging source at $1.5 \mu\text{m}$. The circles ch_i denote the fields of observation relating to each of the laser beams at the fiber output, with a divergence of 1.5 milliradians. At a
 25 distance of one km, a 1.5 meter observation circle is obtained and the 25 circles are practically superposed.

According to one variant of the invention, the field of observation may be varied by virtue of pairs of lenses the distance of which is varied to produce a zoom function and thus enlarge the field of observation enabling, for
 30 example, an extended imaging source of about 5 meters diameter at a distance of 1 km to be generated.

According to another variant of the invention, it is possible, by adjusting the associated optics, to adjust the divergence of these lasers by virtue of diasporameter-type structures formed from sets of two prisms the
 35 orientations of which may be rotated. Their implementation is furthermore very

simple due to the small diameter and the monochromatic nature of the ray. This configuration amounts to changing the direction in which the various prisms face, enabling the extent of the field of observation to be substantially spread at great distance and leading, typically, to an observation region of 4 to
 5 5 meters in width.

Typically, the set of these diasporameters may be used to vary the field from 1.5 to 5 mrad.

The prisms employed may be prisms monochromatic at 1.5 μm and may for example be made of silica.

10 According to another variant of the invention, some of the N amplifying output fibers are recombined into a smaller number M of fibers so as to reduce, if necessary, the number of pupils of the imaging system. This may for example be the case if it is desired to work at higher rates and with more moderate power per fiber. This may also be the case if it is desired to reduce
 15 the number of pupils so as to simplify the system. In this case N is a multiple of M and the combination may be produced using multimode $n \times 1$ or $n = N/M$ fiber couplers $C_{N/M}$. This type of component is commercially available and may be produced to specification. Passive fibers (without laser ions) are then used, the characteristics (core diameter and numerical aperture of the signal at 1.5
 20 μm) of which are identical to those of the amplifying fibers. The output fiber is a passive fiber the diameter and the numerical aperture of which are chosen so as to preserve the overall geometric extent (diameter $\times$ numerical aperture) of the N fibers. Figure 4 shows an example of the amplification chain incorporating this option. Thus from $N \times F_i$ fibers, $M \times F_j$ fibers are obtained as
 25 output.

According to a first example, with a number N equal to 57, each fiber emitting 5 mJ, a number M equal to 3, namely 3 exit pupils, may be had by using a 19×1 coupler.

30 According to a second example, with a number N equal to 56, each fiber emitting 5 mJ, a number M equal to 8, namely 8 exit pupils, may be had by using a 7×1 coupler.

Figure 5 shows a cross-sectional view of the set of diasporameter structures that can be used in a variant of the invention, these being coupled to each beam of 10 mJ output energy. The rotation means R_i are coupled to
 35 two prisms Pr_{1i} et Pr_{2i} at the output of a lens Li .

To form an imaging device, the imaging source is coupled to an imager having an open time window of the order of a microsecond and a spectral window of 10 nm to circumvent the effect on the S/N ratio of parasitic light sources consisting of solar scattering by the atmosphere and that part of
5 the target which is heated to the melting point by the laser weapon.

CLAIMS

1. An imaging device operating at a wavelength near 1.5 microns comprising
 - an imaging source emitting photons for reflection by various objects in a given environment:
 - an imaging receiver collecting the reflected photons;
 - an optical device to adjust the illuminated field from the imaging source, to a target comprising the various objects;and wherein:
 - the imaging source is a pulsed laser imaging source emitting at a wavelength of about 1.5 microns in a spectral band ($\Delta\lambda$) of a few nanometers and delivering a power of between at least a few tens of millijoules and several hundred millijoules, comprising:
 - a source (Ds) emitting a wave having pulses of greater than approximately a few tens of nanoseconds duration;
 - an amplifier assembly (Ampli1, Ampli2, Ampli3) delivering an amplified wave from the wave output from the pulse source;
 - a set of N fibers (Fi) connected in parallel, supplied with the amplified wave, each of the fibers connected in parallel being coupled to an output amplifier.
2. An imaging device as claimed in claim 1, characterized in that it comprises a coupler enabling the energy of the amplified wave to be distributed to the inputs of the N fibers.
3. An imaging device as claimed in claim 2, characterized in that it furthermore comprises an optical system enabling the field of observation to vary from 1 milliradian to several milliradians.
4. An imaging device as claimed in claim 3, characterized in that the optical system comprises a set of N coupled optics at the output of the N fibers.
5. An imaging device as claimed in claim 3, characterized in that the optical system comprises a set of N fibers (F_i) recombined into M output fibers (F_j) by a set of couplers (C_{NM}).

6. An imaging device as claimed in either of claims 4 and 5, characterized in that said optics comprise a pair of lenses and means for adjusting the distance between lenses so as to vary the field.

7. An imaging device as claimed in one of claims 4 to 6, characterized in that said optics comprise a pair of prisms and means for rotating said prisms so as to vary the angular position of each prism relative to the other.

8. An imaging device as claimed in one of claims 1 to 7, characterized in that the amplifier assembly comprises a series of several amplifiers for generating from a signal wave of a few tens of nanojoules an amplified wave of energy greater than at least about ten millijoules.

9. An imaging device as claimed in claim 8, characterized in that the amplifier assembly comprises three diode-pumped fiber amplifiers.

10. An imaging device as claimed in one of claims 1 to 9, characterized in that the fibers are erbium-doped fibers or erbium/ytterbium-codoped fibers.

11. An imaging device as claimed in one of claims 1 to 9, characterized in that it comprises 25 fibers connected in parallel so as to generate an optical beam of about 250 millijoules of energy.

12. An imaging device as claimed in one of claims 1 to 11, the imager having an open time window of the order of a microsecond.