DETECTION OF LASER ULTRASONIC SURFACE DISPLACEMENT BY WIDE APERTURE FIBER OPTIC AMPLIFIER

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Abstract: In the frame of the European Project INCA, CESI is in charge of developing a laser system for the detection of laser induced ultrasounds both in carbon-fibre and metallic components.
The light back-scattered by the surface of the components and the structures – normally encountered in technical and industrial applications – is rather poor in power due to the absorption and diffusion processes, as explained in Reference 1. On the other side, good behaviour in signal to noise ratio of detectors needs quite high level of energy.
One way of solution is to increase the energy of the laser that is the source of the back-scattered light, but this means a very expensive and cumbersome laser system.
This paper proposes a method for amplifying the collected light after the back-scattering from the surfaces.
The choice of developing a fibre optic amplifier relies on its simpler and more rugged mechanical assembly with respect to the more traditional bulk amplifier (for example Nd:YAG), its lighter weight and less sensitivity to misalignment, reduced need of alignment tools, lower cost with respect to a solid state amplification. The instrument designed by CESI is suited for opto-electronic applications that require the signal frequency demodulation for incoherent detection (i.e. with a Fabry-Perot type interferometer) and for opto-electronic applications in general.
Key features of such an amplifier are a wide aperture and a large collecting area, that means an efficient collection of the signal to be amplified. It must be pointed-out that any amplification process adds noise to the input signal: to reduce the added noise it is mandatory to drive the amplifier in condition of saturation, that is to convert the whole energy pumped into the amplifier in amplified signal. By this way the noise added to the signal is negligible and does not affect the effective output of the laser ultrasonic tests.

Introduction: Laser ultrasonic technique applied to the inspection of composite materials usually requires a single mode detection laser with a long pulse (at least 50 μsec) and a high peak power (at least 1 KW).
The need of a long pulse is due to the flying time of the ultrasound echoes inside the composite materials: over all this time the detection laser must check the profile of the surface of the sample.
The high power is due to the attenuation of the laser beam by the surface of the sample under inspection.
This type of laser has a high cost, especially if the required repetition rate – essential to reduce the inspection time of a component - is over 100 Hz, that makes necessary to pump the laser with laser diodes, instead of flash lamps.
To develop a more cost-effective detection laser, a high power Nd:YAG laser has been excluded because of no potentiality on the market and low technical innovation, while a low power Nd:YAG demonstrator was excluded because of again the low technical innovation and no ultrasonic results of good value.
As suggested by CESI and agreed by all the INCA Partners, it has been started the development of the fibre optic amplifier for post-collection amplification, with the aim of providing an innovative and cost-effective device.
A scheme of the post collection amplification is shown in Figure 1:

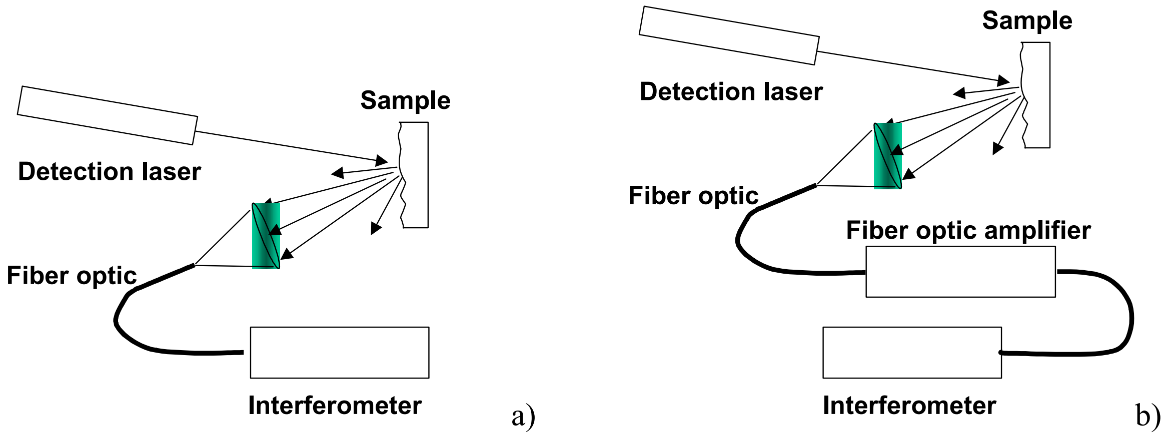


Figure 1 - Post collection amplification: a) Scheme of the detection instrumental chain without post-collection amplification, b) Scheme of the detection instrumental chain with post-collection amplification

The fibre optic amplifier is inserted in the path of the collected light; the gain of the optical amplifier allows the use of a less powerful detection laser, while decreasing a lot the cost of the system.
The fibre optic amplifier designed by CESI, is based on a Ytterbium doped fibre, that converts a fraction of the light of the pumping diodes, absorbed by its dopants, into light with the same wavelength and phase of the incoming signal via the stimulated emission effect.
This effect is related to the presence of atoms in an excited state, due to the pumping process. The interaction of the incoming signal photons with the excited atoms forces them to undergo a transition to a lower state energy: the energy lost by each atom is released as a photon twin of the incident one.
A confirm of the validity of the post-collection amplification approach is the system designed by Lockeed Martin, covered by the Patent reported in Reference 2.
Results: A dedicated software, written in the Matlab language, has been developed by CESI to simulate the performances of the fibre optic amplifier. The instrument designed by CESI is suited for opto-electronic applications in general. As an example, the amplifier can be employed to enhance the laser signal back-scattered by the atmosphere and the ground in systems applied to the control of environmental problems.
The design characteristics of the optical amplifier are the followings:

- Single Mode – Double Cladding
- CW operation
- small signal gain ~ 30 dB @ 1064 nm
- input fibre diameter 210 μm, Numerical Aperture N.A. 0.45
- fibre length 40 m
- 5 W pumping diodes @ 920 nm
- Output signal/Amplified Spontaneous Emission ASE noise ~ 20 dB @ 50 μW input power.

The numerical simulation led to the optical design of the fibre optic amplifier shown in Figure 2.

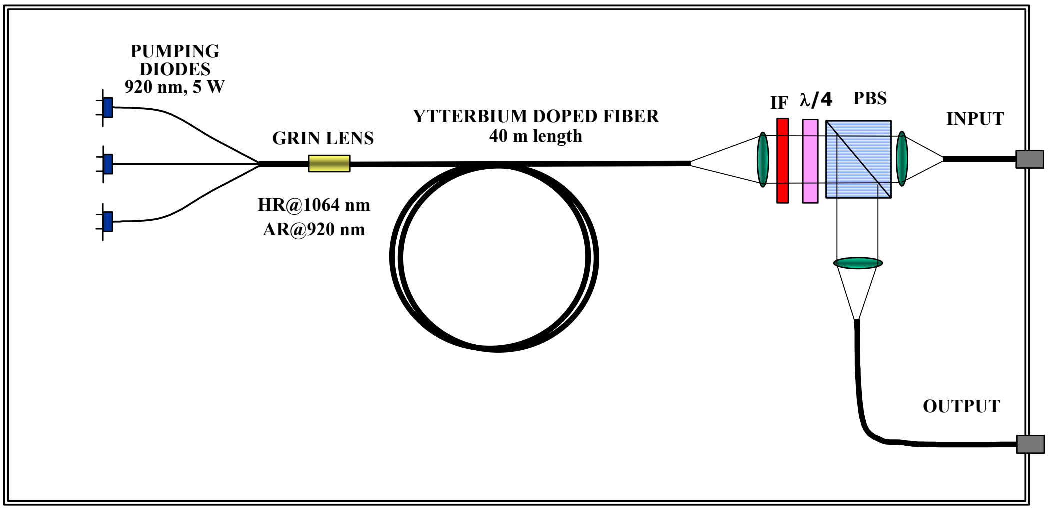


Figure 2 – Optical scheme of the fibre optic amplifier (IF = Interference Filter, PBS = Polarising Beam Splitter)

The emission spectrum of the laser diodes, measured with an optical spectrum analyser, is shown in Figure 3. The measured characteristics of the laser diodes are in accordance with the performance declared by the supplier, JDS Uniphase, while the spontaneous emission spectrum of the Single Mode Ytterbium doped fibre supplied by OFS (19 Schoolhouse Road, Somerset, NJ, www.ofsoptics.com), pumped with the 920 nm laser diode, is shown in Figure 4.

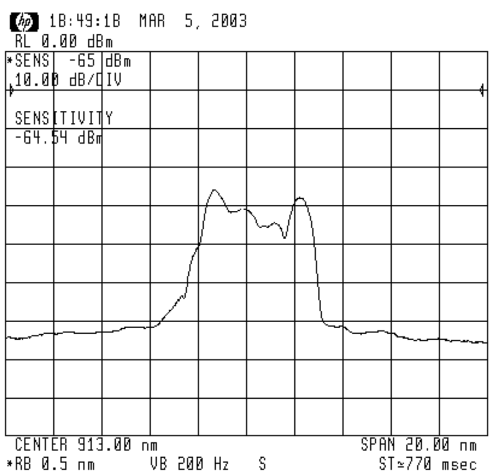


Figure 3 – Emission spectrum of the laser diode emitting at 920 nm

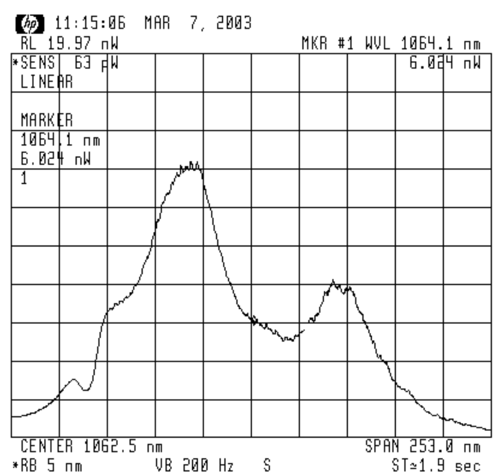


Figure 4 - Spontaneous emission spectrum of the Ytterbium doped fibre, pumped with the 920 nm laser diode.

The first prototype has been assembled in a simplified way, as shown in Figure 5, employing as input for the signal to be amplified one of the fibres available for the connection of the pumping diodes to the Ytterbium doped fibre. In the simplified scheme the signal that must be amplified travels through the Ytterbium fibre only one time instead of two as foreseen by the original optical scheme. In fact, during the preliminary experimental tests on the double path, in managing the high power level circulating into the amplifier, the failure of the grin lens occurred, probably due to the absorption of the pumping light by the special coating deposited on this component, that must provide both HR – High Reflectivity @ 1064 nm and AR – Anti Reflection @ 920 nm.

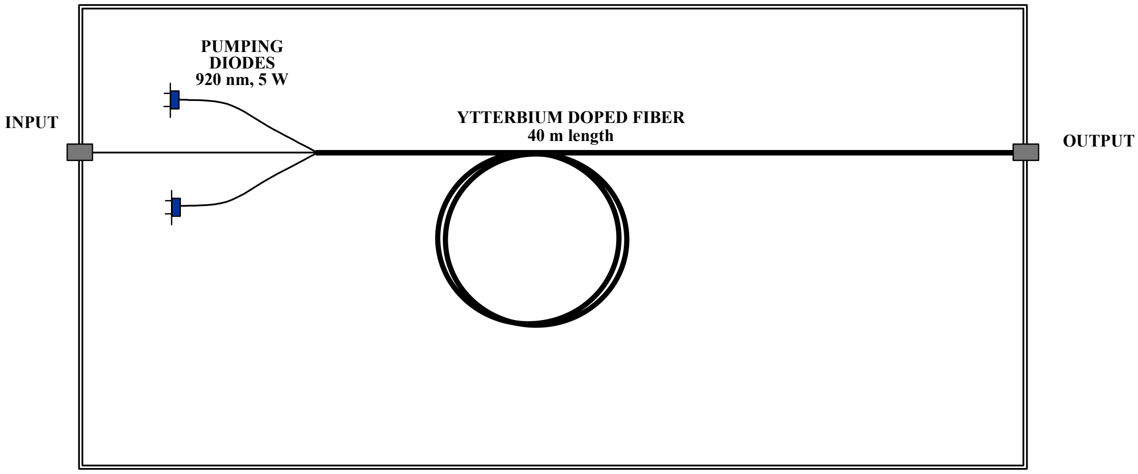
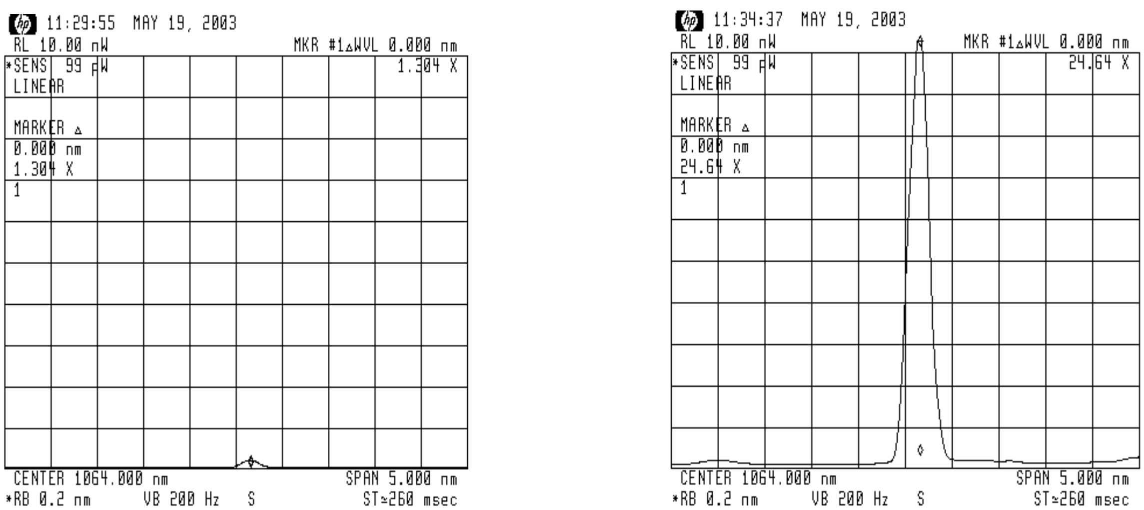


Figure 5 – Simplified optical scheme of the prototype of the fibre optic amplifier

The amplification of the signal, as it has been obtained with the single path prototype, is shown in Figure 6.



a) b)

Figure 6 – a) Signal before amplification; b) Signal after amplification

The gain of the amplifier, measured with the optical spectrum analyser, is of about 15 dB with a N.A. of the input fibre shown in Figure 5 of 0.2. The reasons limiting the amplifier gain can be explained as follows:

- the signals travels through the Ytterbium fibre only one time instead of two as foreseen by the original optical scheme, due to the failure of the grin lens
- stimulated Brillouin scattering limits the pumping power of the amplifier, since this effect gives rise to a lasing action at the scattered wavelength.

Alternative components and schemes have been investigated to overcome the limitations to the gain of the fibre optic amplifier.

An important aspect to be carefully considered is the termination of the fibre: the termination of the fibre must be protected with a connector providing an antireflection coating to avoid unwanted laser action and instabilities of the amplifier due to the fraction of the signal reflected by the fibre end. A similar result can be obtained lapping the fibre end at an angle of few degrees with respect to the optical axis of the fibre.

Moreover the grin lens can be replaced by a fibre Bragg grating, that acts like a “mirror” written inside the fibre. The effectiveness of this component in reflecting a significant fraction of the input signal must be verified.

The new scheme proposed to overcome the limits of the fibre optic amplifier (lack of the double pass due to the failure of the grin lens coating – limited gain due to self oscillation of the amplifier, caused by stimulated Brillouin scattering) is shown in Figure 7.

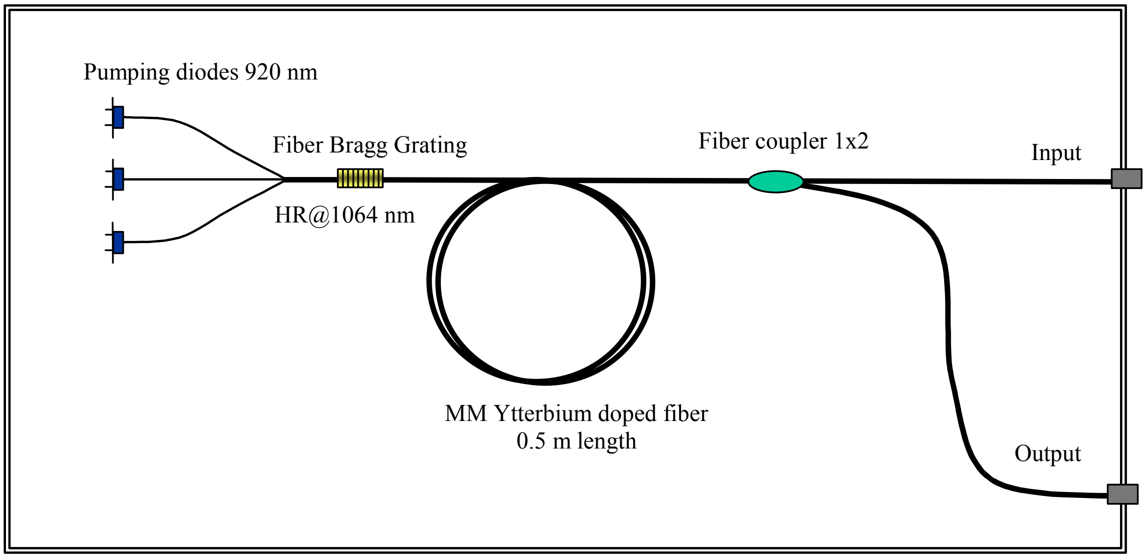


Figure 7 - New scheme of the fibre optic amplifier

Key elements of the new optical amplifier are:
- the fibre Bragg grating, that replaces the grin lens
- the multimode MMYtterbium doped fibre, supplied by INO Quebec (2740 rue Einstein, St-Foy – Quebec, G1P4S4 Canada, www.ino.ca) that replaces the Single Mode Ytterbium doped fibre.

A simplified input/output stage can be built-up by means of a 1x2 fibre coupler. The two arms are unbalanced, with a coupling ratio of 10/90. The input fibre is connected to the 10 % arm, while the output fibre to the other one: by this way the 90% of the amplified signal will be extracted from the amplifier.

The fibre Bragg grating reflects the input signal, already amplified after the first passage through the doped fibre; as the reflection bandwidth of the fibre grating is very narrow, the ASE noise out of this bandwidth will not be reflected, avoiding its amplification.

After the reflection the input signal travels through the doped fibre a second time, completing its amplification.

The characteristics of the fibre Bragg grating are:

- Central wavelength 1064 nm
- FWHM 0.2 nm
- Reflectivity > 96 %
- Core diameter 35 µm

The multimode Ytterbium doped fibre will reduce the influence of the stimulated Brillouin scattering, that is correlated with the length of the active medium (the radiation produced by the scattering propagates along the doped fibre amplifying itself): in fact the strong absorption of the pumping wavelength, due to the large core diameter and to the dopant level, allows to reduce the length of the gaining fibre to 0.5 m or less.

The characteristics of the multimode Ytterbium doped fibre are:

- Single clad structure
- Cladding diameter 225 µm
- Core diameter 38 µm
- N.A. 0.12
- Absorption @920 nm >100 dB/m

It must be pointed-out that the core dimension of the fibre Bragg grating and of the doped fibre are not perfectly matched (the multimode fibre Bragg grating has not been provided on a custom base), but an acceptable coupling of about 80 % between them can be reasonably expected.

The overall gain of the amplifier has been evaluated to be the same of the previous scheme, as the absorbed pumping power is the same: this means that an equal number of Ytterbium atoms are excited and available for amplification.

Discussion: It has been pointed-out in the Abstract section that any amplification process adds noise to the input signal. To limit the added noise, the amplifier designed by CESI operates in condition of saturation, that is the whole energy pumped into the amplifier is converted in amplified signal.

We would like of analysing the reasons why the Ytterbium doped fibre optic amplifier is expected to provide good signal to noise performances.

First, in a 4 levels system, as it is the Ytterbium doped fibre, ASE noise is proportional to the density population of the excited atoms at the upper level N2, as explained in Reference 3. Driving the amplifier in saturation, that is with a high signal level, the population in N2 decreases approaching the depletion.

In fact $N2 = N2^{o}$ (1+I/Is), see Reference 4, where $N2^{o}$ is the population inversion without signal, I is the intensity of the signal and Is is the saturation intensity.

The design of the amplifier foresees a value I/Is that can be estimated as 100 ÷1000, that means a value for N2 approaching the depletion.

Second observation, ASE emission spectrum of Ytterbium:silica is very wide, about 180 nm, that is 40,500 GHz; in comparison it can be observed that the ASE emission spectrum of Nd:YAG is 0.8 nm that is 180 GHz.

As a consequence the ASE power density of Ytterbium:silica falling into the bandwidth (30-60 MHz) of the detector of the laser ultrasonic interferometer is very low. By this way the noise added to the signal is negligible and does not affect the effective output of the laser ultrasonic tests.

Figure 8 gives a graphic explanation of the bandwidth relationships as discussed above.

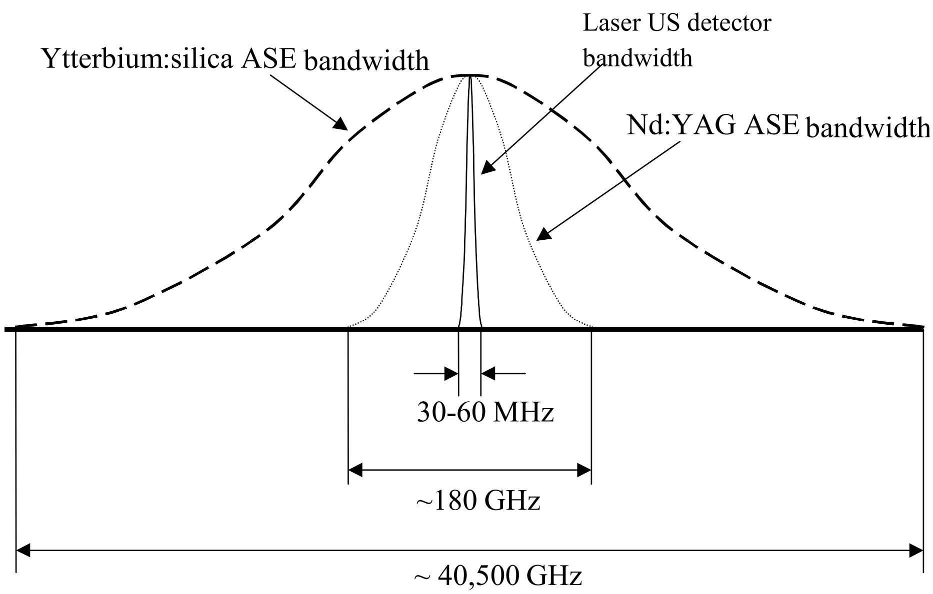


Figure 8 – Graphic explanation of the relationships between Ytterbium ASE bandwidth, Nd:YAG ASE bandwidth and laser US detector bandwidth.

Conclusions: The paper presents an innovative laser system for detecting ultrasonic surface displacements.

The fibre optic amplifier is now completely designed in its second version, while the needed components have been acquired. The experimental results obtained employing the second version amplifier will be presented at the Meeting in Montreal on August 2004 and published immediately after.

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References:

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