New fiber laser and coherent lidar developments at Onera

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Onera has been developing lidars for military, environmental and aeronautical applications for more than 30 years. The main instrumental developments deal with wind / wake vortex lidar for airport and environmental applications, lidar vibrometer for identification purpose or seismology applications, dial and supercontinuum lidars for gas detection and identification, airborne lidar for navigation sensors.

In parallel, the team has a strong involvement in fiber laser technology in order to develop laser sources suitable to lidar applications. The main objective are the power scaling of fiber laser sources so as to increase lidar range, measurements accuracy and/or measurement rate. This implies the development of new active fibers, new technologies to overcome the stimulated Brillouin scattering (SBS) threshold or architectures involving coherent combining of amplifiers. Other developments deal with new wavelengths narrow linewidth fiber lasers or supercontinuum lasers to address particular gas species detection.

In this paper, we focus on innovative fiber laser developments and their integration in lidar systems for wind or gas monitoring. We also present new developments for two lidar applications: lidar vibrometer for structural damage assessment, and supercontinuum lidar for remote spectroscopy. Two other topics (Wake vortex detection and Wind sensing using coherent combining), are presented in dedicated papers.

Fiber Laser developments for lidar applications

Fiber lasers have some advantage over other solid state lasers: free-space optics are avoided, sparing lengthy alignment procedures and yielding compact setups. Sources around 1.5 µm benefit of the development of components coming from the telecom industry and can be low cost. They are also well adapted for Lidar and on board applications thanks to their intrinsic vibration-resistant design.

Onera has developed a fiber amplifier delivering 1 kW peak power laser emission at 1.54 µm with narrow linewidth and high spatial beam quality. The amplifier is now commercialized by Keopsys, a french SME. Onera is currently developing a new generation fiber laser for long range lidar applications based on a 3 stage MOPFA (master oscillator power fiber amplifier). The two first stages are included in a commercial 15 µJ fiber laser. The third stage uses a polarization maintaining large mode area (LMA) Er/Yb fiber with SBS mitigation strategy based on strain distribution. The current achievement is 2.5 W average power, 10 kHz, 600W peak power, which, at the time of the writing of this paper was only limited by the available pump power (Figure **1Erreur ! Source du renvoi introuvable.**).

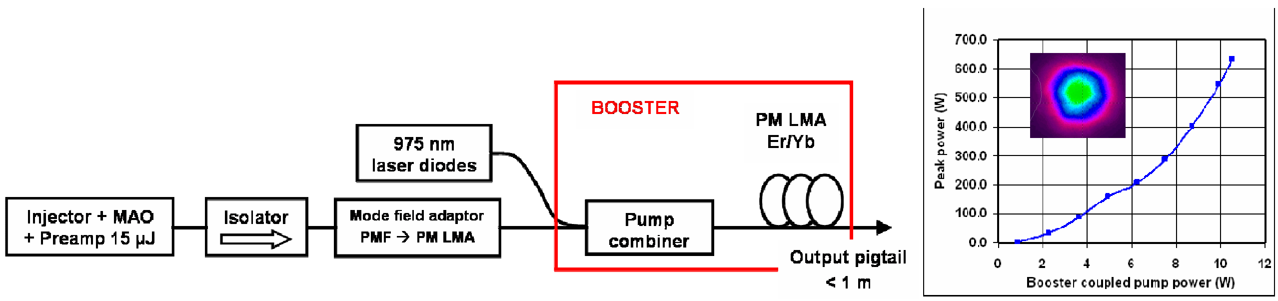

Figure 1 : left : fiber laser set up, right : peak power as a function of the coupled pump power, inset: near field at the pigtail output.

Producing narrow linewidth high peak power from a single fiber is challenging due to fiber damage, thermal limitations, and nonlinear effects such as SBS. Coherent beam combining (CBC) of fiber amplifiers allows overcoming these limitations: an array of fiber amplifiers is actively phase locked and combined into a single beam while keeping the optical properties of a single fiber, such as good beam. Most of the studies concerning CBC have been performed in CW regime. . However, some lidar applications require pulsed source. One of the questions raised on the feasibility of CBC in a pulse regime was the existence of detrimental phase variations inside the pulses. This point was checked and characterized for the first time to our knowledge, in an experiment involving active CBC in the 100's ns pulse regime [1]. The frequency-tagging technique initially proposed for the CW regime [2] has been adapted to the pulse regime by introducing a CW signal leak between the pulses. Pulses have been combined with 95% efficiency, a residual phase error of λ=27, and no significant beam quality degradation (Figure 2). The use of such a CBC laser in a wind lidar has then been demonstrated at Onera with 250ns pulses with no degradation of the carrier to noise ratio compared with a single source of the same characteristics [3].

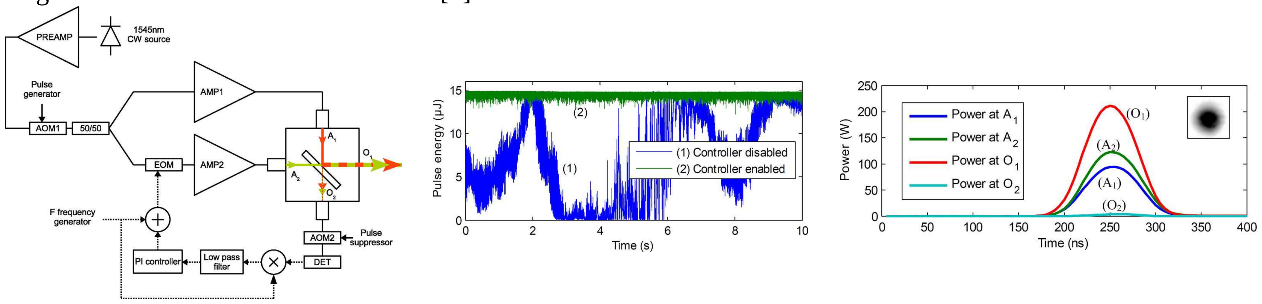

Figure 2 :Left :Experimental setup of CBC of two pulsed fiber amplifiers. PREAMP, preamplifier; AMP1 and AMP2, amplifiers; A1 and A2, amplifiers outputs; O1 and O2, CBC outputs; DET, photodetector. Middle: Evolution of combined pulses' energy with controller disabled and enabled. Right : Measured pulse profiles before and aftercombination (constructive and destructive interferences). Outputbeam profile is shown as an inset.

Onera fiber laser development for space applications targets at building a fiber laser demonstrator for CO_2 sensing with DIAL lidar. Specifications were derived from ESA A-scope mission requirements. Unfortunately, the identified CO_2 lines are located in the L amplification (close to 1579 nm) where Erbium cross sections are small (Figure 3 left). Consequently, MOPFA (Master Oscillator, Power Fiber Amplifier) designs suffer from low fiber non-linear threshold and low efficiency. High precision on the CO_2 concentration measurement requires narrow linewidth and the laser is primarily limited by SBS. SBS threshold can be improved by: reducing fiber length, reducing effective Brillouin gain or increasing effective area. Due to the small cross-sections of Erbium in L band, large doping concentration or large fiber length are required. The preliminary lab experiment is based on 3 stages MOPFA using commercial fibers. The fibers are resonantly core pumped at 1480nm, thus allowing relatively short fibers (a few meters) and flat excited population profiles. This reduces C-band amplified spontaneous emission (ASE) generation and improves efficiency. This approach is compatible with excellent beam quality. Erbium doped Aluminosilicate has been chosen as the cross-section at 1579nm for this glass is twice as large as phosphosilicate glass (Figure 3left). The last stage is built using a 3.6m long commercial Erbium doped LMA fibers core pumped using a wavelength multiplexer. The beam propagation parameter (M^2) was measured to be smaller than 1.2. The SBS threshold was observed to be close to 500W peak power. Thanks to a SBS mitigation strategy based on strain distribution, the output peak power was increased up to 1.7kW. Due to the low saturation level of the last stage, the slope efficiency reaches 23% at a pulse repetition rate of 4 kHz but increases to more than 30% at 20 kHz. To the best of our knowledge this is the highest peak power transform limited pulse generated in the L-band [4].

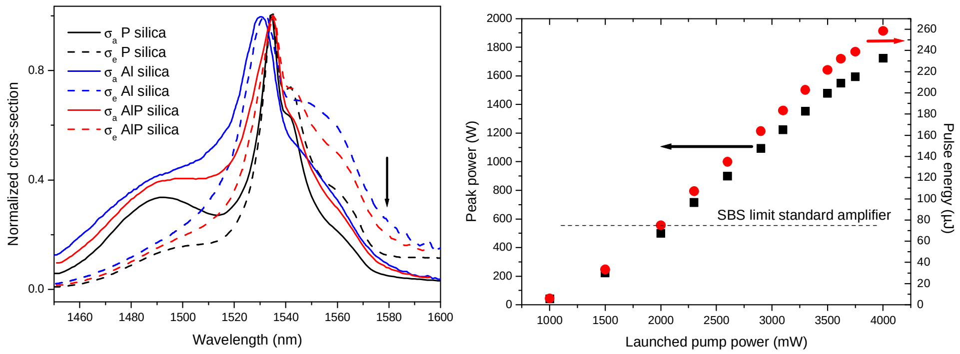

Figure 3 : Left: Erbium absorption and emission cross section in Aluminosilicate and phosphosilicate glass. Right: peak power and peak power

Other development addresses 2 µm fiber lasers. These fiber lasers may be used for materials processing, lidar, gas-sensing, spectroscopy or medical surgery. Basically, we are interested in synchronously-pumping single-mode (longitudinal and transverse) OPO. Indeed, a 2 µm pump is well suited because of the strong absorption of OP-GaAs or ZGP crystals in the near IR. This kind of fiber laser can also be used to pump with ultrashort pulses highly nonlinear fibers such as chalcogenide fibers to generate radiation in the 3-5 µm band. Thulium-doped or thulium/holmium-codoped silica fiber lasers are good candidates for the generation of ultrashort pulses around 2 µm due to the large gain bandwidth (more than 100 nm) available from the silica glass host. Onera has developed a high power all-fiber single-mode thulium-doped mode-locked laser (Figure 4). The oscillator generates transform-limited pulses with 62 pJ energy and 4.5 ps duration at 1960 nm. Solitons are amplified in a short highly Thulium doped single-mode fiber amplifier pumped into the core at 1560 nm. At the output, the solitons energy reaches 32 nJ (358 mW average output power) and the pulse peak power is 9.1 kW with a small self phase modulation distortion. The amplified soliton duration is about 3.5 ps at the maximum output power and the slope efficiency of the amplifier is 13 % with respect to the injected pump power [5] [6] .

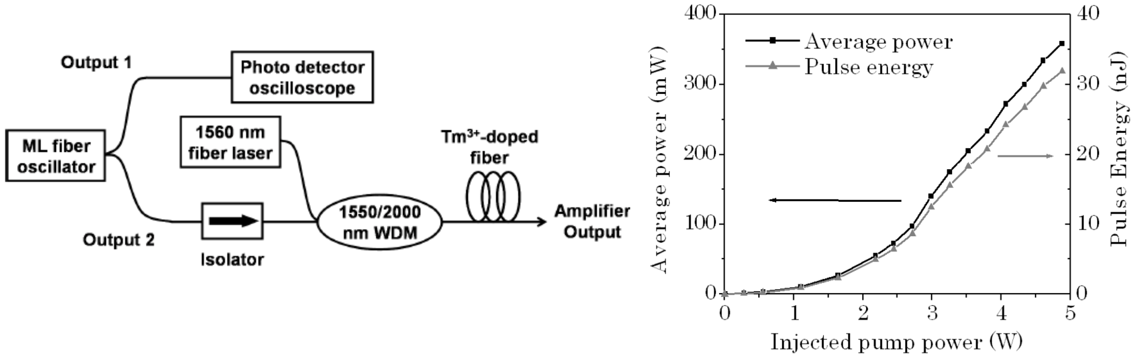

Figure 4 : left : 2µm Mode-locked fiber laser setup , right: Average power and pulse energy versus injected pump power.

Supercontinuum sources in the mid-infrared have potential applications to spectroscopy and material characterization. Supercontinuum light extending up to 4000 nm has been efficiently generated in fluorozirconate glasses (ZBLAN) with 10.5 W power using an amplified nanosecond pulsed laser diode at 1550 nm [7]. As the dispersion wavelength of the fiber is close to 1700 nm, pumping at 1550 nm does not directly allow the generation of solitons. A first approach is thus to pump a piece of single mode fiber in the anomalous dispersion regime to generate the solitons and shift them to the anomalous dispersion regime of the ZBLAN fiber [7]. Another approach is to use a high power femtosecond laser at 1600 nm [8]. In that case, the pulse broadens through self phase modulation up to overlap with the ZBLAN anomalous dispersion regime. In both cases, the pump wavelength is very close to the zero dispersion wavelength of the fiber to maximize the spectrum broadening. However, a limited amount of power is generated beyond 2500 nm (30%) which is the relevant spectral window for many applications. We have reported [9] on what we believe to be the first demonstration of direct pumping of ZBLAN in the anomalous dispersion regime at 2 µm to generate a supercontinuum extending up to 3800 nm (Figure 5). The pump source is an amplified thulium gain switched fiber oscillator at λ_p = 1995 nm emitting 7 ns pulses at 10 kHz with peak power up to 9 kW. The output fiber of the pump source is butt-coupled to the fluorozirconate fiber. This is a 5.3 m ZBLAN fiber with numerical aperture NA=0.22 and 10.6 µm core diameter. The coupling ratio corrected from the Fresnel reflections reaches 65 %.

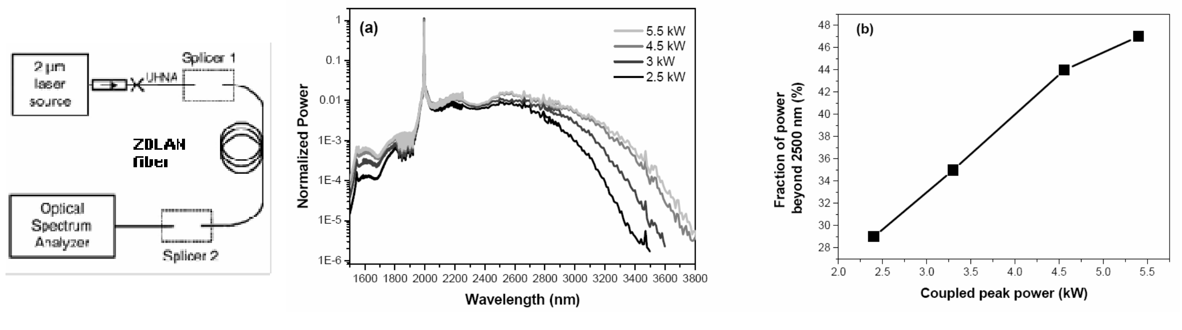

Figure 5 : Left: experimental setup. A high pass filter is used beyond 2500 nm to avoid aliasing and reject the stray light. Middle : Experimental spectra after propagation through the ZBLAN fiber for increasing coupled pump power. The supercontinuum is measured with a high resolution optical spectrum analyzer up to 2400 nm and a monochromator coupled to a MCT detector beyond. Right : Fraction of supercontinuum power generated beyond 2500 nm.

We observe a supercontinuum extending up to 3800 nm for 5.5 kW coupled peak power (when taking the supercontinuum long wavelength edge at -30 dB from the continuum) (Figure 5). The average power out of the fiber is 490 mW. Due to the dispersion at the pump wavelength, the spectra have little broadening towards the short wavelengths side (550 nm). From the experimental spectra, we calculate the fraction of light generated beyond 2500 nm. It continuously increases from 28% (for 2.5 kW peak power) up to 47 % for 5.5 kW peak power(Figure 5). This is 1.5 times larger than the conversion efficiency reported by [7].

Gaz detection

The development of supercontinuum laser sources opens attractive perspectives for broadband spectroscopy and atmospheric remote sensing. Indeed, their high spectral power density and spatial coherence make them well suited for standoff measurements. The spectral region covered by the supercontinuum source presented above is rich in atmospheric species of interest, among which many volatile organic compounds.

Such sources can be used for range-integrated gas quantification experiments (Figure 6 left). We have examined a situation where the gas species present in the optical path are known, and where the goal is to quantify their concentration-path-length (CPL) products. Onera proposed tools to predict the precision of range-integrated concentration measurements of multiple gas species and an iterative signal-processing tool, baseline insensitive, to estimate the concentration-path-length using supercontinuum absorption spectroscopy. This estimator also takes into account the signal nonlinearity induced by the limited resolution of spectrum analyzers. These are improvements compared to previously applied estimators, which were initially developed for high-resolution applications with a known, or calibrated, spectral baseline [10]. Statistical tests on simulated and experimental signals (Figure 6 middle and right) have shown that the proposed estimator is near optimal, yielding the true CPL values with a precision close to the best possible value.

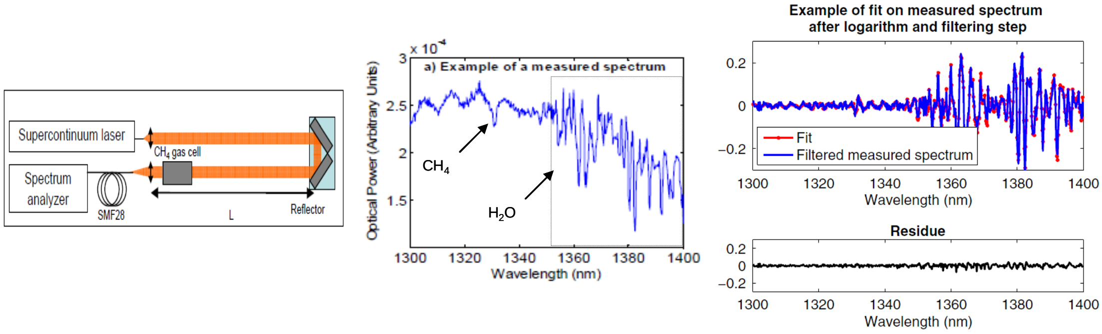

Figure 6 : Left : experimental setup of a supercontinuum range-integrated quantification experiments. Middle : Supercontinuum signal (measurement): 501 sampling points, 1 nm FWHM resolution, SNR=130. The gas mixture is made of H_2O (numerous peaks beyond 1340 nm) and CH_4 (isolated peak at 1330 nm). Right : Example of fit on measured spectrum, frequency sampling periods is ν_s= 0.5 nm^{-1}.

Vibrometry

Over recent years there has been a growing interest in building frequency analysis for earthquake and structural engineering fields. The direct applications are (1) to define the modal characteristics of existing buildings in order to model their seismic response, (2) to monitor the long-term variation of their structural health, and (3) to detect and localize changes in the structure such as those produced by earthquake damage or explosions. Coherent lidars are able to provide data by remotely measuring the vibration velocities using ambient vibrations excitation. Their assets are (1) to avoid the entrance of personnel in a potentially damaged building thereby mitigating safety issues (2) to provide a rapid method of acquiring data of various targeted buildings. We have assessed the capability of lidar to properly extract the full modal parameters of reinforced concrete buildings, including mode shapes, using multiple lidar measurements on the building front [11].

A frequency analysis has been performed on several buildings using simultaneous measures with sensitive velocimeter sensors and a coherent lidar sensor. Ambient vibrations recordings by velocimeter were processed using the Frequency Domain Decomposition (FDD) method in order to define the frequencies and mode shapes of the target building, and compared to velocity, frequency and mode shapes data obtained with the coherent lidar.

For that purpose, we have developed and field tested of a 3-path lidar vibrometer (Figure 7 left). Autonomous operation has been demonstrated during a vibration measurement campaign over five buildings in the French city of Grenoble at 200m range. By comparing the vibration data obtained by sensitive in situ velocimeter sensors and coherent remote lidar vibrometer sensor, we observe a good fit of the values of modal frequencies and of mode shape detected by both approaches (Figure 7 middle & right). Even if the noise level is higher for lidar (10^{-6} m/s) than velocimeter (10^{-7} m/s), most of the existing buildings could be checked by this remote sensing method opening up the way to sensors capable of rapid monitoring of a whole urban area.

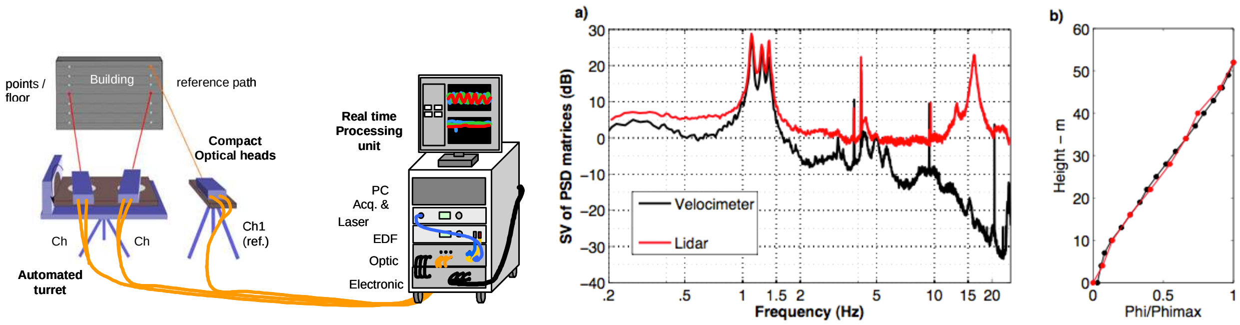

Figure 7 : Left : Lidar vibrometer experimental setup with multiple measurement beam configuration. Middle and left : singular value decomposition using the FDD method (a) and correspond mode shape for the first bending mode (b) computed at the ARPEJ 2 building. Symbols on (b) correspond to the location of recordings by Lidar or velocimeters

Conclusions and prospects

We have presented a number of fiber laser developments at Onera and their application in lidar sensors for remote sensing applications. The fiber gain medium geometry enables single mode emission and intrisic thermal effects mitigation which translate in high pulse repetition rate (i.e. high average power). Fiber amplifiers also exhibit good efficiencies and wavelength tunability.

However non linear effects can be detrimental to the beam quality. In applications requiring narrow linewidth and near diffraction limited beam, the increase in peak power is limited due to Stimulated Brillouin Scattering but can be overcome using various techniques such as those mentioned in this paper. Moreover, MOFPA architecture offers interesting design flexibility since the pulse shape and duration and pulse repetition rate can be independently set depending on the application requirements. This design is therefore very convenient for systems such as Doppler lidar (e.g. wind lidar) and DIAL lidar.

Non linear effects in fibers can also be exploited to generate broadband emission with excellent beam coherence and spatial quality. Thanks to the high spectral power density and spatial coherence of supercontinuum lasers, sensors for spectroscopy at standoff ranges are likely to become a common technique in the future. The access to the IR spectral band also opens prospects for their application in environment and security issues.

Fiber lidar architecture enables compact designs and reliable setups even in vibrating environment favorable to their deployment on the field or on airborne platforms. Fiber Doppler wind lidars are already installed as a stand alone sensor on windfarms. As reliability and measurement range are progressing a fast pace, fiber lidar sensors are deemed to become even more common in the very near future e.g. on airports, weather forecast and science facilities or petrochemistry plants.

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