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First demonstration of a 12 DFB fiber laser array on a 100 GHz ITU grid, for underwater acoustic sensing application

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ABSTRACT

We report for the first time a multiplexed array of 12 distributed feedback fiber lasers (DFB FLs) on a single optical fiber, separated by only 100 GHz (0.8 nm) in the C-band. These lasers are pumped by a 200 mW laser diode at 1480 nm with no apparent impact on the sensor noise floor despite the fact that the residual reflections from adjacent gratings may be enhanced due to the smaller wavelength separation. Each DFB FL, especially developed for serial multiplexing, exhibits low lasing threshold typically between 1 and 2 mW, low intensity noise and very low frequency noise (less than 30 dB re 1 Hz²/Hz at 1 kHz from optical carrier). From these experimental results, extension to 32 DFB FLs array (on 100 GHz ITU grid) multiplexed on one fiber will be discussed.

Keywords: Distributed feedback fiber laser, optical fiber sensors, acoustic sensors, fiber laser acoustic sensors, multiplexed sensing, hydrophone

1. INTRODUCTION

Fiber optic hydrophones array have advantages over conventional piezoelectric ones¹ such as fully optical array without need of electrical power supply in the array part. However existing interferometric optical sensor technology is complex and is relatively bulky. Fiber lasers based hydrophone could afford compactness and lightness.² They consist of an optically pumped narrow-linewidth distributed feedback fiber laser, which is exposed to acoustic pressure, producing laser frequency modulation that are interrogated using an unbalanced interferometer.³ The resolution of this type of sensors is only limited by the intrinsic frequency noise of the laser. DFB FLs are particularly suited for compact hydrophones array due to their low diameter hydrophone capability and their simple multiplexing capability when they are in series on a single fiber.^{4,5} However cascading them may create unwanted external optical feedback in each laser cavity. These external reflections from the side lobes of adjacent Bragg gratings (adjacent with respect to the wavelength) and from Rayleigh scattering in the connecting fiber may result in excess intensity and frequency noise as well as occasional self-pulsing.^{6,7}

These fiber laser sensors have already been used in multiplexed hydrophone arrays, even if improvements on the size of the mechanical system are still to be made. In recent years, multiplexed arrays of sensors consisting of four,⁸ five⁹ and eight DFB FLs¹⁰ have been reported, the maximum number of sensors being sixteen with a spectral separation of 1.6 nm (200 GHz).¹¹ The number of DFB FLs, which can be multiplexed on a single fiber is limited by the losses accumulated during the propagation, the crosstalk between DFB FLs and reflections due to Rayleigh backscattering or bad splices. Tikhomirov⁶ and Rønnekleiv⁷ reported that the interaction between neighboring lasers seriously influences frequency noise because each DFB FL experiences the discrete reflection from the side lobes of adjacent Bragg gratings.

The work detailed in this communication describes the realization of an array of 12 DFB FLs spectrally separated by only 100 GHz and pumped at 1480 nm by 200 mW for hydrophone applications. This communication is organized as follows. First, a typical optical array architecture based on multiplexed DFB FLs is described in

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section 2. Then, the performances in terms of intensity noise and frequency noise of an array of 12 DFB FLs are experimentally measured in section 3. Finally, the possibility of increasing the number of cascaded DFB FLs is discussed in section 4.

2. DFB FL SENSOR ARRAY SYSTEM

Typical array architecture for underwater acoustic sensing application shown in figure 1 is composed of two parts: the left one could be remoted on a land station with all the electrical components; the other right part consists only of optical components and is immersed underwater. The fiber lasers used in the antenna are DFB FLs as described in figure 2. They are optically pumped at 980 or 1480 nm (in our configuration) through a wavelength division multiplexer (WDM) after having travelled across a potentially long lead fiber (up to 10 km). The acoustic pressure is converted through appropriate strain transfer to the fiber laser cavity into a frequency modulation of the lasing frequency, then into a phase modulation by an interferometer. The information coming from each hydrophone is separated by the dense wavelength division demultiplexer (DWDM) and is finally read by the very low noise demodulation system with a heterodyne method.

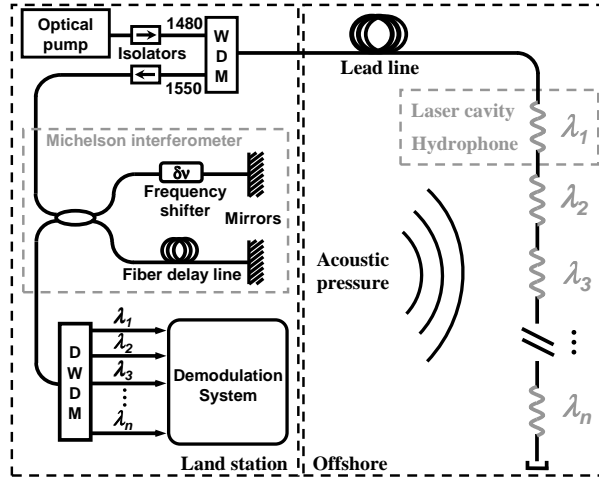


Figure 1. Typical System overview with Optical array & Opto-electronic Supply & Processing unit.

2.1 DFB FL

Each laser cavity is formed by a short (3-5 cm) rare-earth doped fiber on which a unique fiber Bragg grating, with a π -phase shift near the center, has been written using UV light. The laser wavelength is defined by the resonance condition of the Bragg grating and corresponds to the Bragg wavelength, which is determined by the pitch Λ of the grating and the effective index n_{eff} of the photowritten fiber:

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda. \quad (1)$$

The wavelength of each laser can be selected during the grating photo-inscription by adjusting the pitch of the grating and may be anywhere within the emission manifold of the gain medium. For erbium doped DFB FLs, which is our case, this enables wavelength division multiplexing across the C-band from 1535 nm to 1565 nm. It is thus possible to use a commercially available DWDM based on the International Telecommunication Union (ITU) grid to isolate each wavelength from the FL array. It is well known that the external reflections from the side lobes of adjacent Bragg gratings are the most serious problem for multiplexing several DFB FLs on a single fiber. This may result in excess intensity noise and frequency noise and occasional self-pulsing.^{6,7} Thus, to minimize laser instability, the reflection spectrum of our DFB FLs are apodised to reach less than -30 dB of reflection for wavelength of the adjacent lasers.

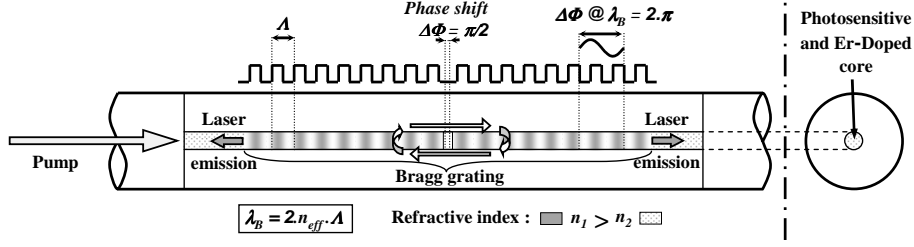


Figure 2. Simple sketch of an erbium doped DFB FL.

2.2 Sensitivity to strain

When a fiber Bragg grating (FBG) is longitudinally strained by an amount $\varepsilon_z = \Delta\Lambda/\Lambda$, for which the pitch Λ of the Bragg grating varies, the Bragg wavelength λ_B (or equivalently the laser frequency ν_B) changes according to the equation

$$\frac{\Delta\lambda_B}{\lambda_B} = \frac{\Delta\nu_B}{\nu_B} = [1 - P_e] \cdot \varepsilon_z, \quad (2)$$

where $P_e = (n^2/2)[p_{12} - v(p_{11} - p_{12})]$ is the effective strain-optic constant, n is the effective index, p_{ij} are the Pockel's coefficients of the stress-optic tensor and v is the Poisson's ratio. For silica fibers,¹² P_e equals to 0.22. Then the wavelength shift due to strain is equivalent to

$$\Delta\lambda_B = 0.78 \cdot \varepsilon_z \cdot \lambda_B. \quad (3)$$

Without any other external perturbation, this wavelength shift at 1550 nm is

$$\Delta\lambda_B \approx 1,2 \text{ pm}/\mu\varepsilon_z, \quad (4)$$

where $\mu\varepsilon_z = 10^{-6} \varepsilon_z$ is defined as a microstrain.

2.3 The Deep Sea State Zero

For underwater acoustic applications, the aim of this array of hydrophones is to measure acoustic signals as low as the level of the acoustic noise floor of quiet ocean, conventionally represented by the so-called Deep Sea State Zero¹³ (DSS0), which is about 160 $\mu\text{Pa}/\text{Hz}^{1/2}$ (44.5 dB re 1 $\mu\text{Pa}/\text{Hz}^{1/2}$) at 1 kHz.⁵ This acoustic pressure P acts like a longitudinal strain on the Bragg Grating of the DFB FL via the equation

$$\varepsilon_z = (2\nu - 1) \times \frac{P}{E}, \quad (5)$$

where ν is the Poisson's ratio and E the Young modulus. For silica,¹⁴ $\nu = 0.17$ et $E = 70 \text{ GPa}$, which corresponds to $\varepsilon_z = -1.5 \times 10^{-15}/\text{Hz}^{1/2}$ at 1 kHz, so that the DSS0 naturally induces for the laser a frequency noise of around 230 $\text{mHz}/\text{Hz}^{1/2}$ at 1 kHz from the optical carrier. The frequency noise of DFB FLs at 1 kHz is around a few tens of $\text{Hz}/\text{Hz}^{1/2}$, which is several orders of magnitude higher than the previous DSS0 induced frequency. This intrinsic sensitivity is too small to measure the DSS0 but can be amplified through a specific DFB FL mechanical packaging system, which converts external pressure to longitudinal strain with order of magnitude of 2 nanostrain/Pa. It finally leads to a frequency noise corresponding to DSS0 of around 34 $\text{Hz}/\text{Hz}^{1/2}$ at 1 kHz from the optical carrier. This explains why the resolution of this type of sensors is only limited by the intrinsic frequency noise of the laser.

As shown in table 1, the Bragg resonance frequency (at 1550 nm) is very sensitive to environmental perturbations, such as temperature or hydrostatic pressure, which depend in an important way on the depth of the water. An ideal mechanical system must be only sensitive to dynamical pressure and insensitive to other perturbations.

In this paper, the lasers are not packaged in such a system. The demonstration only concentrates on multiplexing DFB FLs in an array, with optical frequencies separated by 100 GHz. The hydrophone aspect using these cavities is being studied in a second step by Thales Underwater Systems.

Table 1. Sensitivity of the Bragg resonance to external perturbations at 1550 nm.

Sensitivity	Value	Unit
longitudinal strain	1,2	pm/ $\mu\epsilon_z$
	150	MHz/ $\mu\epsilon_z$
temperature	10	pm/ $^{\circ}\text{C}$
	1,25	GHz/ $^{\circ}\text{C}$
hydrostatic pressure	-4,5	pm/Mpa
	-375	MHz/Mpa

3. ARRAY OF 12 DFB FLS SEPARATED BY 100 GHZ

The experimental setup used to cascade and measure noises of the DFB FLs is shown on figure 3. The lasers operate at wavelengths from channel 29 (1554.13 nm) to channel 18 (1563.05 nm) on a 100 GHz spaced ITU grid. They are spliced together in descending order of the channel number, with 2 meter-long standard single-mode fiber between them. The total length of single-mode fiber from the pump laser diode to the last DFB FL is around 30 m. Each DFB FL exhibits low lasing threshold typically between 1 and 2 mW, an efficiency of about 0.2-0.4 % and an emission power of around 550 μW for 200 mW of pumping power. Figure 4(b) shows the different light-pump power for 4 of these lasers.

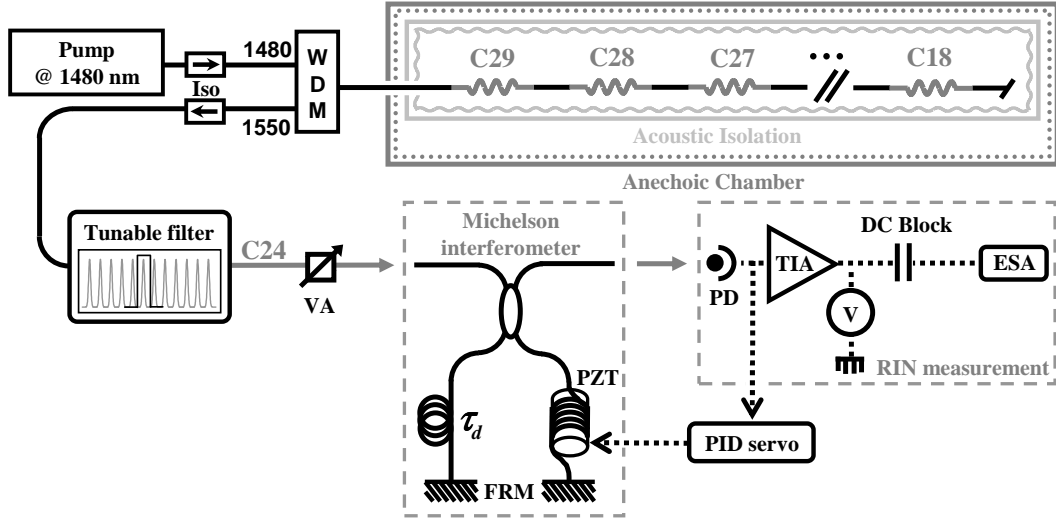


Figure 3. Experimental setup. Iso: Isolator; VA: Variable attenuator; FRM: Faraday rotating mirror; PZT: Piezoelectric transducer; PD: Photodiode; TIA: Low noise transimpedance amplifier; V: Voltmeter; ESA: Electrical spectrum analyzer.

DFB FLs are pumped through a 1480/1550 WDM by a laser diode emitting at 1480 nm with 200 mW onto the first laser. The pump wavelength choice at 1480 nm instead of 980 nm is determined by the low background losses of the commercial standard single-mode fiber at 1480 nm.

To measure the intrinsic noises of the array, the 12 DFB FLs are isolated from environmental noises by an acoustic-isolated box placed onto an anti-vibration table inside an anechoic chamber (only to improve the acoustic isolation). Moreover, the use of an optical isolator at the output from the 1550 branch of the WDM avoids additional external reflection.

The optical spectrum of the lasers array has been measured using an optical spectrum analyzer (Anritsu MS9710B) with a resolution of 0.07 nm as shown in figure 4(a). The pump light is absorbed each time it passes through a laser, thus decreasing for the next laser, the pump power. However a good flatness of the optical

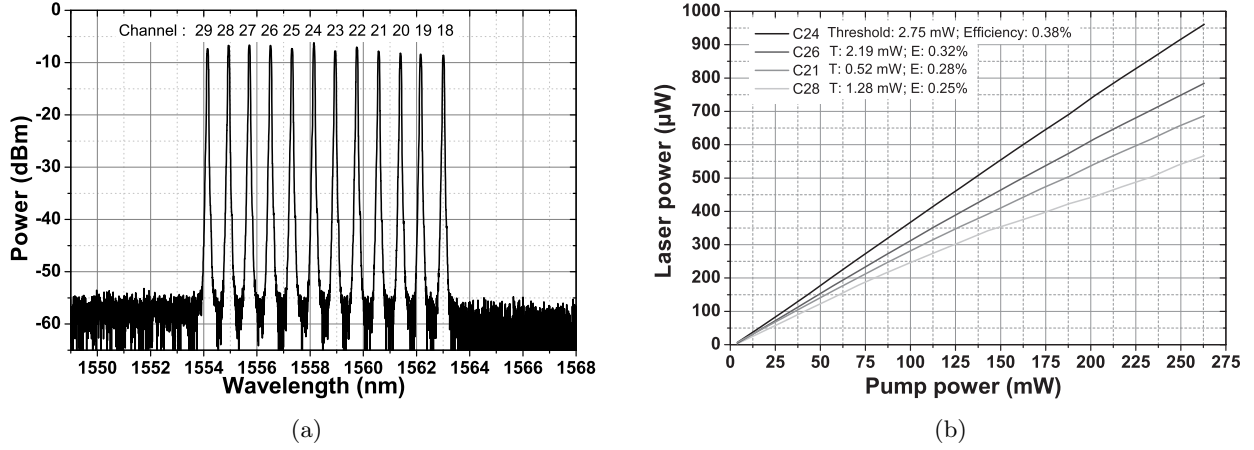
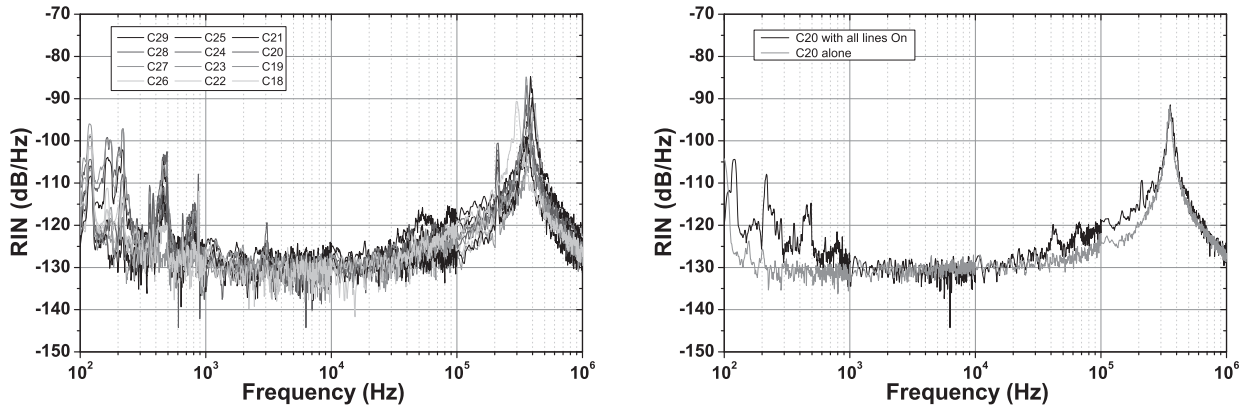


Figure 4. (a) Optical spectrum of the 12 DFB FL array pumped at 200 mW, measured with a 0.07-nm resolution; (b) Light-pump power of 4 lasers.

spectra is observed. This can be explained by the fact that all the lasers have low pump absorption and do not have the same threshold power and efficiency (figure 4(b)).

The relative intensity noise (RIN) is measured using a classical method,¹⁵ which takes into account the shot noise of the detection system. It consists in measuring the power spectral density (PSD) of the photocurrent generated by the detector by means of an electrical spectrum analyzer and normalizing the PSD by the average photocurrent. In order to measure the RIN of individual FL, a tunable optical filter is placed at the output of the array so that individual channel could be filtered out and measured independently one from the other. The RIN of each channel in the array is traced on the same figure 5(a). There are no significant differences between their RIN. Figure 5(b) compares, at the same pump power (same relaxation frequency), the RIN of the channel 20 when it is running alone and the RIN of the same channel 20 but when the 12 channels are operating altogether. Several remarks concerning these results deserve to be made. Both measurements have the same noise floor of about -130 dB/Hz and the same RIN of -91.5 dB/Hz at the relaxation peak. Nevertheless, when the 12 channels are operating altogether, we can observe an excess of noise for C20, for frequencies below 1 kHz and just below the relaxation peak. That could be explained by the reflections from bad splices in the FL array and from Rayleigh backscattering induced along the fiber.



(a) RIN of the 12 DFB FL array pumped at 200 mW. (b) RIN of the isolated C20 compared to the frequency noise of C20 when all lines are operating.

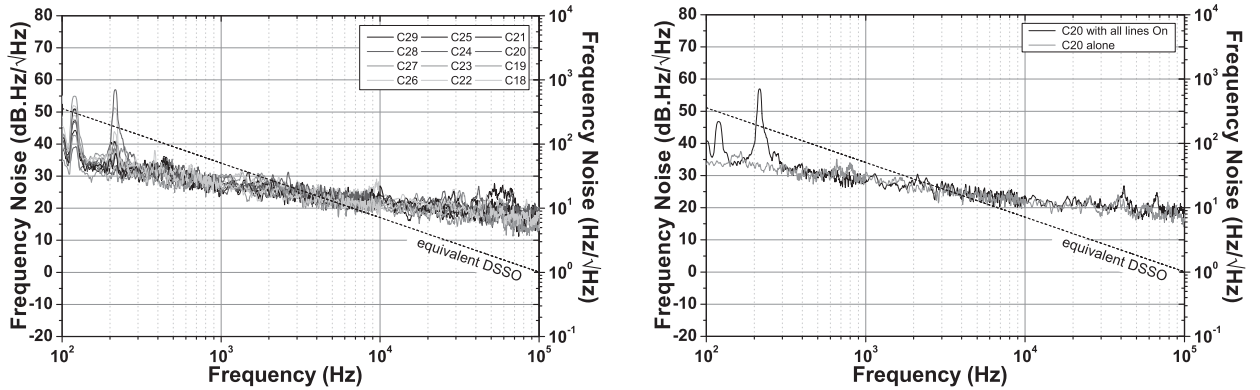
Figure 5. RIN comparison.

The frequency noise of each channel is measured one by one, as previously using a tunable optical filter to selectively isolate each individual signal from the whole response of the channel array. The remaining laser signal is routed to a 40-m single-mode-fiber-length unbalanced Michelson interferometer, which is biased in quadrature thanks to a piezo-electric transducer and a PID servo, in order to linearly convert the laser frequency fluctuations into intensity fluctuations, which are proportional to the path imbalance. Faraday rotating mirrors, which reflect the light at the end of the interferometer arms, ensure the alignment of the polarization at the output. The PID parameters have been set so that the servo only compensates slow environmentally-induced laser fluctuations. The PSD of frequency noise $S_\nu(f)$ is then obtained by a simple RIN measurement with the equation

$$S_\nu(f) = \frac{f^2}{4 \sin^2(\pi f \tau_d)} RIN_{MI}, \quad (6)$$

where RIN_{MI} is a RIN measurement at the output of the interferometer and τ_d is the delay time of the interferometer.

By enclosing the interferometer inside an acoustically isolated chamber and inside a Faraday chamber, we suppressed further pick-up in the delay coil.



(a) Frequency noise of the 12 DFB FL array pumped at 200 mW. (b) Frequency noise of C20 alone compared to the frequency noise of C20 when all lines are operating.

Figure 6. Frequency noise Comparison.

The frequency noise of each channel in the array is traced on the same figure 6(a) with the equivalent DDS0. There are no significant differences between their frequency noise. It is worth noting that the frequency noise of this type of laser does not depend on the pump power. This property is important when multiplexing them as they do not receive the same pump power. Figure 6(b) compares the frequency noise of the channel 20 when it is alone and the channel 20 when all the 12 channels are running for the same pump power. It reveals no noticeable change in the noise level above 300 Hz while below this value any measurement remains very dependent on the environmental conditions which are difficult to filter at such low frequencies.

4. DISCUSSION

Without considering any crosstalk between DFB FLs due to unwanted reflections from the secondary lobes of the Bragg gratings, there are several constraints that limit the number of DFB FLs that can be cascaded into an array. Among them, we can notice the fiber length separating the different laser cavities and/or of the lead fiber. This length parameter increases noises and the power budget of the system. It will also affect the available number of channels within the ITU grid when using erbium doped fiber laser as the larger the number of channels is, the longer is the array. Between 1525 and 1565 nm, it would be possible to multiplex 90 DFB FLs¹¹ on a 50 GHz ITU grid if we do not consider the length constraint. With DFB FLs separated by 100 GHz, this number decreases obviously by a factor of two; it is then possible to multiplex 44 DFB FLs. An important result of this

paper is that no crosstalk could be obtained with such a wavelength separation in the configuration previously mentioned.

Let us consider now a bad threshold lasing power of 3 dBm that our lasers exhibit and a reasonable 1-dB losses per device, which include both absorption pump depletion and splice losses. With an available commercial pump laser diode, which provides a power of 500 mW (27 dBm) at 1480 nm, it is possible to drive 20 DFB FLs ($8 \text{ dBm} + 19 \times 1 \text{ dB} = 27 \text{ dBm}$), since a laser works at 3 times (6 mW) its pump power threshold.

With our pump system consisting of a pump laser diode at 1480 nm and a WDM, the available pump power for the array could be around 450 mW (26.5 dBm). Our experimental results show that it is easily possible to reach total losses per device of 0.8 dB. Thus, it is possible to drive 19 DFB FLs. We hope to improve the quality of splices and to reduce the total losses per device to 0.6 dB permitting to cascade on a single fiber up to 32 DFB FLs.

5. CONCLUSION

In this communication, we have described the operating principle of a fiber laser sensor array. We have reported the low intensity noise and very low frequency noise (less than 30 dB $1 \text{ Hz}^2/\text{Hz}$ at 1 kHz from optical carrier) of an array of 12 DFB FLs spectrally separated by 100 GHz on ITU grid and pumped by 200 mW at 1480 nm. With more recent implementations being currently under development, we expect to achieve an array of 32 DFB FLs. This technology has important applications to all optical sensing.

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