Underwater ultrahigh scan-rate quasi-distributed acoustic sensing system

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Abstract

The common maximum pulse repetition rate (PRR) of a reflectometric-based system is determined by its longest delay.

In DAS & Q-DAS, the PRR is bound by the system length (L):

$$f_{scan} = f_{c-max} \equiv v_g/2L$$

Taking advantage of the sparse nature of a Q-DAS impulse response, multiple pulse responses, generated from different pulses, can be interleaved without overlapping, yielding an enhanced PRR.

We term our methods Array Matched Interrogation (AMI) and Coded Array Matched Interrogation (C-AMI) and demonstrate a record interrogation rate of 5MHz over a 1km long system.
We were able to successfully identify ultrasonic acoustic waves (over 12kHz) in the underwater medium at the far end of a 1km fiber.

Optical Setup

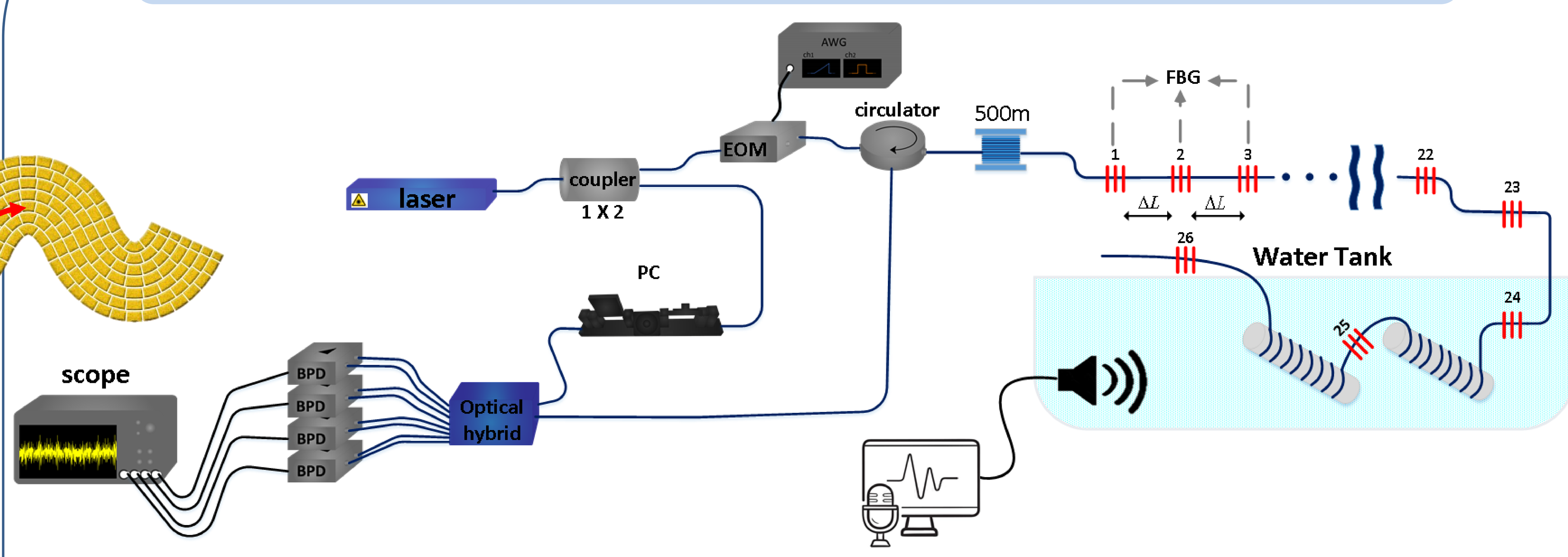


Fig. 1. A coherent quasi-distributed sensing system. PC: Polarization Controller. BPD: Balanced Photo-Detector. FBG: Fiber Bragg Grating. AWG: Arbitrary Waveform Generator. $\Delta L = 20m$.
A fiber containing 26 evenly spaced FBGs was connected to the optical interrogator. The last two sections were wrapped around a mandrel and placed inside a water tank. The two mandrels were subjected to external acoustic signal generated by a submerged ultrasonic source (Teledyne UTS-9000).

Motivation

Many sea mammals use acoustic waves for communication and allocation:

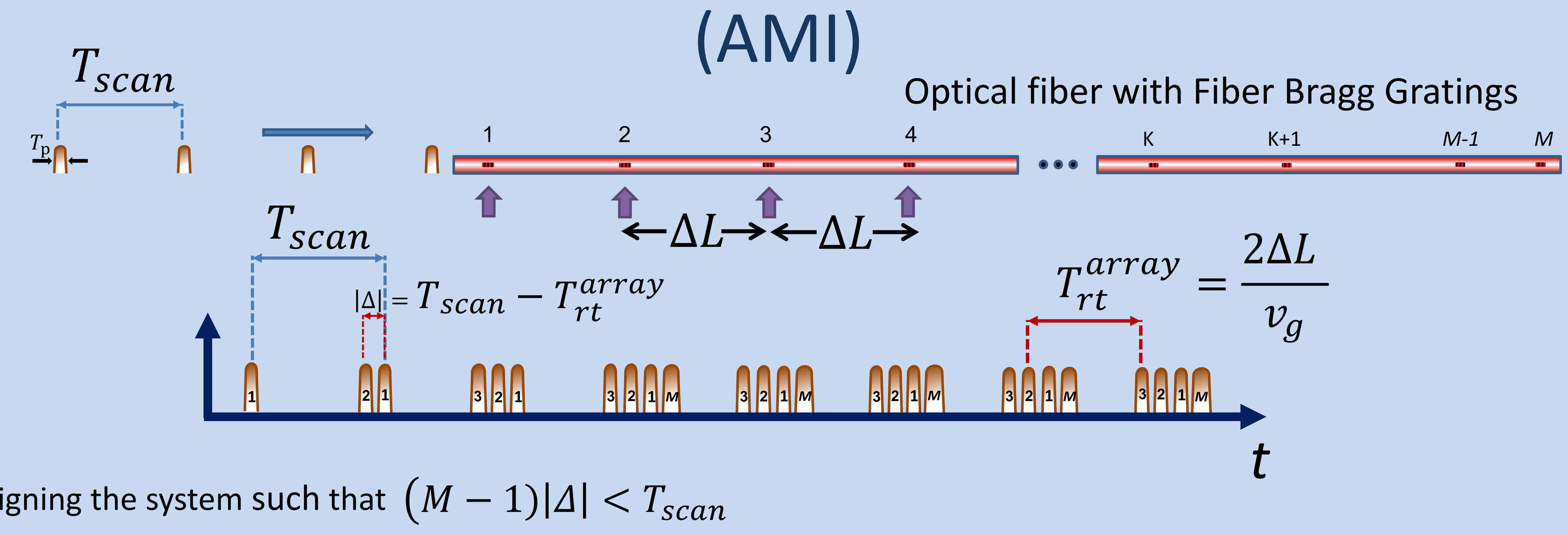
- The striped dolphins, for example, use frequency modulated whistles ranging to more than 20 kHz and echolocation clicks.
- The approximate frequency range of bottlenose dolphin whistles is 0.2 to 24 kHz (Reynolds & Rommel, 1999).
- The frequency range for echolocation clicks is 0.2 to 150 kHz (Reynolds & Rommel, 1999).
  The lower frequencies are used for echolocating objects that are at a distance. As the dolphin moves closer to an object, it can increase the frequency of its echolocation to learn more about the object.

Underwater Acoustic Communication:

- JANUS - a standardized protocol to transmit digital information underwater using acoustic sound.
  It uses 900 Hz to 60 kHz.

Underwater Noise Pollution: "Soundscape of the Anthropocene Ocean", Science, 2021.

Array Matched Interrogation (AMI)



Designing the system such that $(M-1)|\Delta| < T_{scan}$ result in non-overlapping returns.

M reflectors array

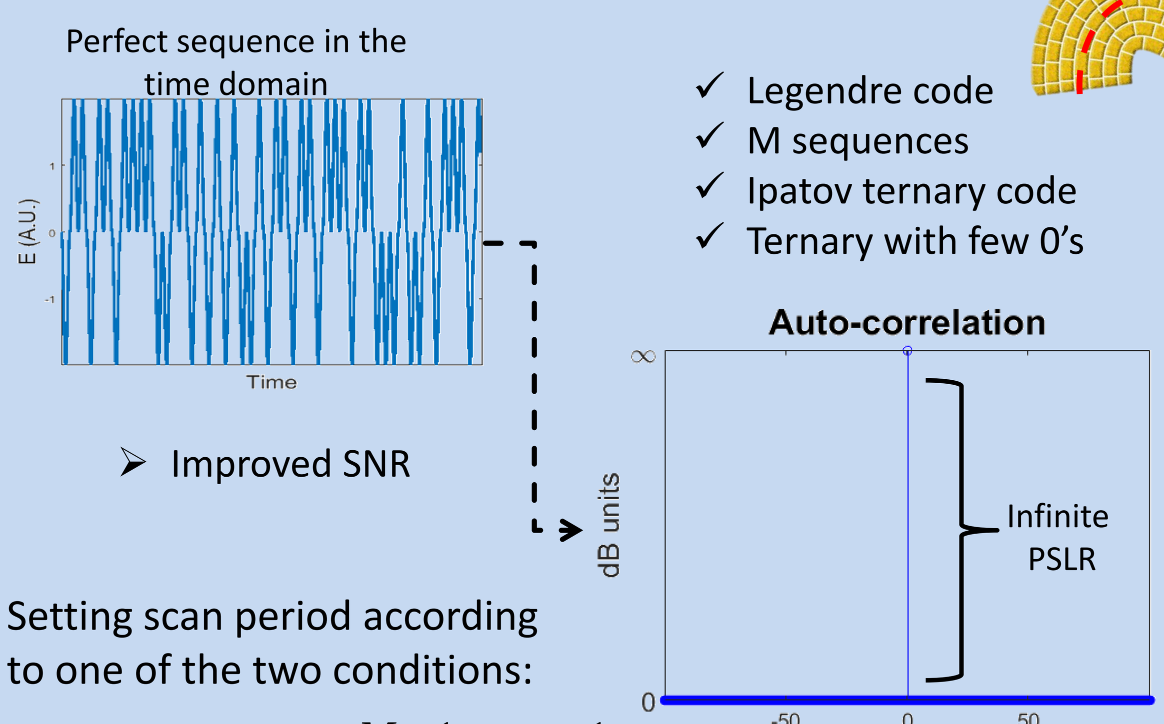
Demonstrated scan rate enhancement factor

$$r_{o.c.} = f_{scan}/f_{c-max}$$

*o.c.=> Over Clocking

Demonstrated $r_{o.c.}$	Platform	Method	Publication year	Reference
X2	DAS	FDM	2015	He, Q., et al. *IEEE Photonics Technology Letters* 27.20: 2158-2161
X2	Q-DAS	NFB	2021	Chen, Y., et al. International Conference on UK-China Emerging Technologies (UCET). IEEE.
X3	Q-DAS	FDM	2019	Zhang, Yi Xin, et al. Optical Fiber Technology 53: 101995.
X3	Q-DAS	TDM	2020	Wang, Z., et al. IEEE Sensors Journal 20.21: 12739-12743.
X5	DAS	FDM	2017	Chen, D., et al. Journal of Lightwave Technology 35.10: 2037-2043.
X5	Q-DAS	TDM	2020	Wang, Z., et al. Optics Express 28.26 : 38465-38479.
X16	DAS	FDM	2016	Iida, D., et al. Optical Fiber Communication Conference. OSA.
X20	Q-DAS	TDM	2022	Arbel, Nadav, et al. Optics Express 30.7: 11647-11659.
X24	DAS	FDM	2021	Jiang, Jialin, et al. Optics Letters 46.3: 685-688.
X51	**Q-DAS**	**TDM**	**2022**	**Arbel, N., Tur M. and Eyal A. OFS-27 conference**

Coded Array Matched Interrogation (C-AMI)



- ✓ Legendre code
- ✓ M sequences
- ✓ Ipatov ternary code
- ✓ Ternary with few 0's

➢ Improved SNR

Setting scan period according to one of the two conditions:

$$T_{rt} + T_p \le T_{scan} \le \frac{M-1}{M-2}T_{rt} - \frac{1}{M-2}T_p$$

or

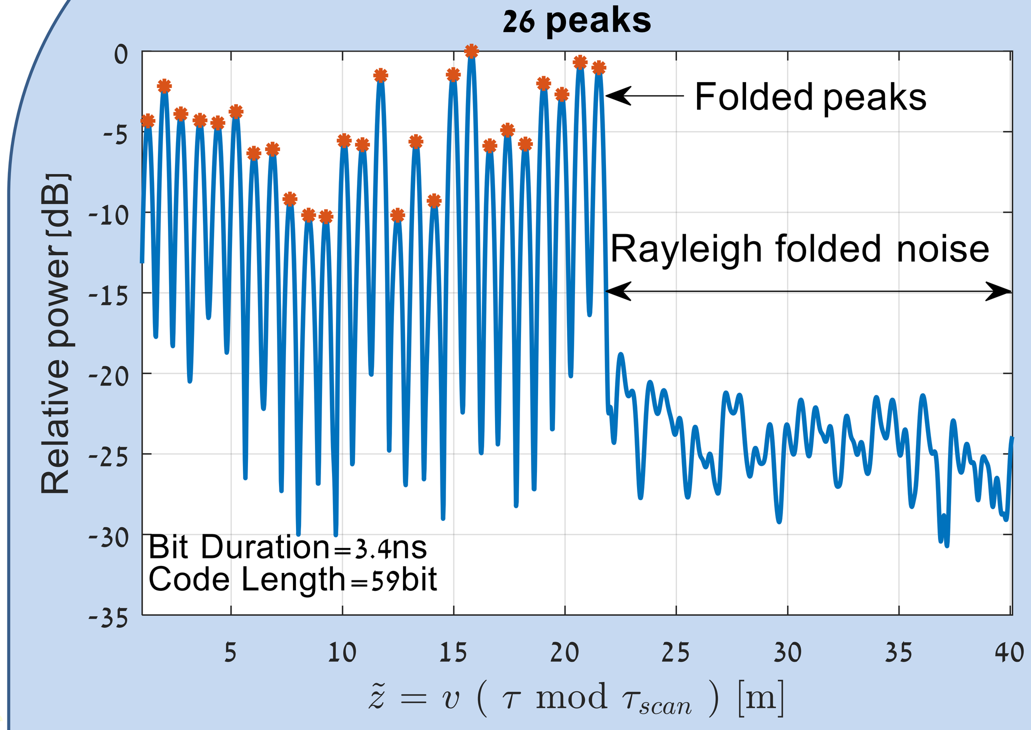
$$\frac{M-1}{M}T_{rt} - \frac{1}{M}T_p \le T_{scan} \le T_{rt} - T_p$$

Results in a non overlapping compressed pattern.

Results

Average power of all segments [dB]

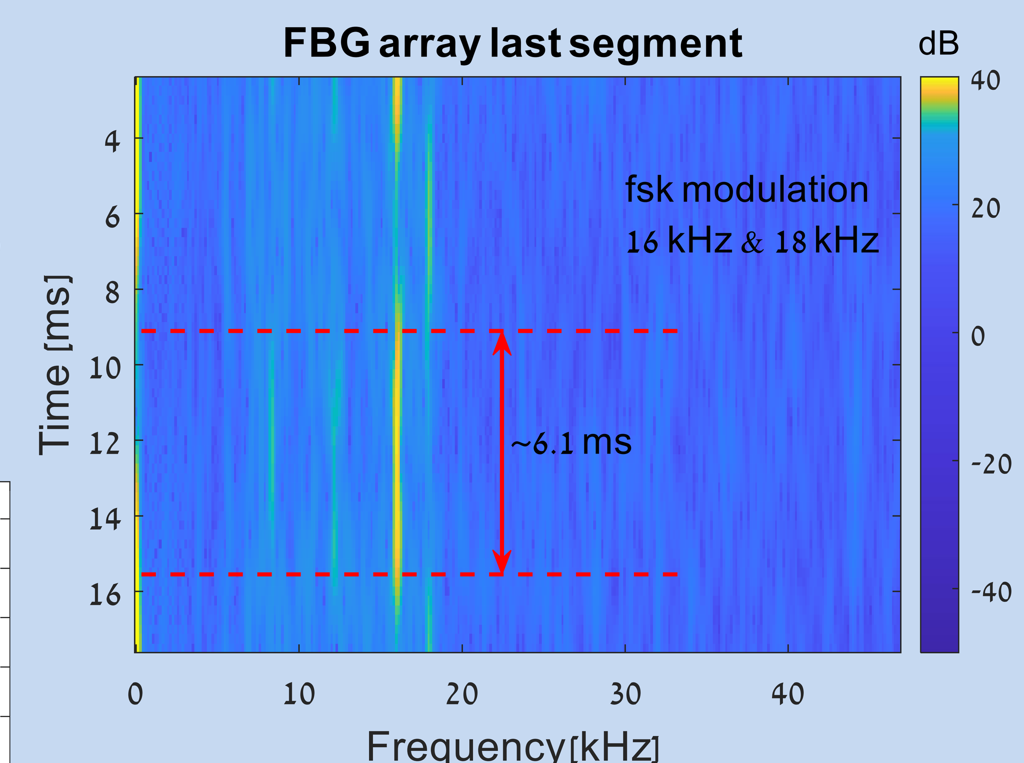
26 peaks



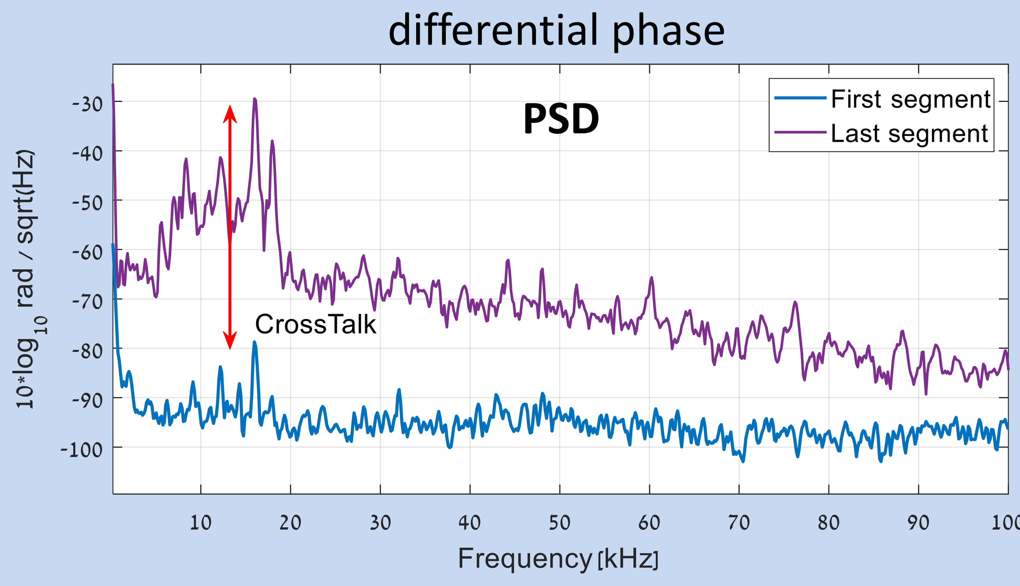
$$r_{o.c.} \approx {}^{1km}/_{20m} = {}^{5MHz}/_{100kHz} = 50$$

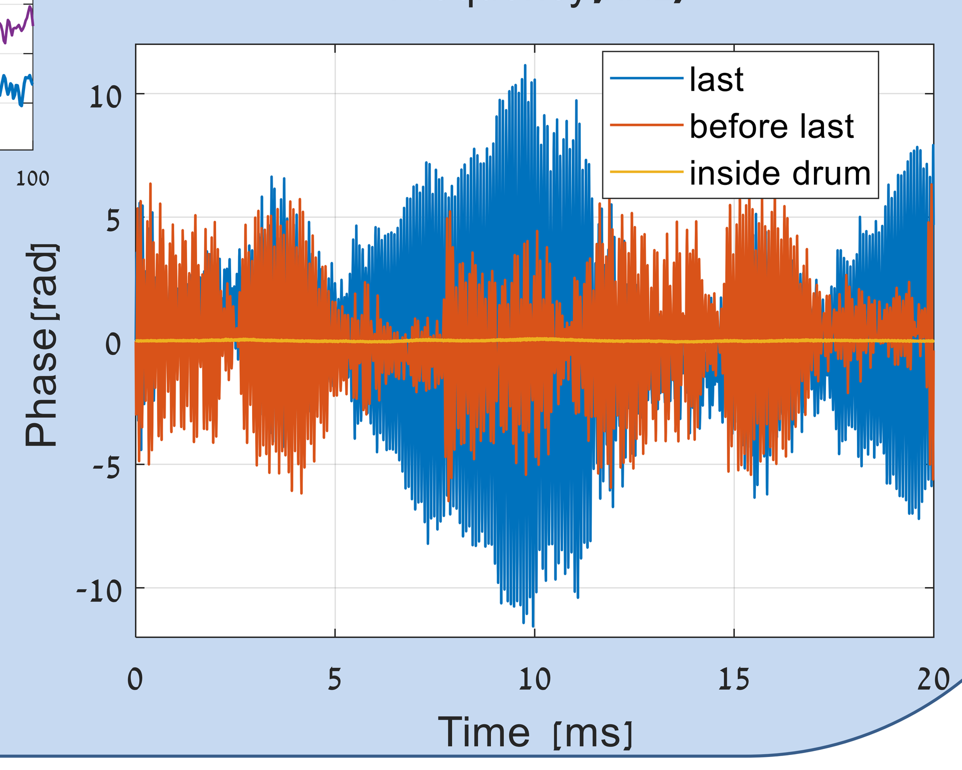
FBGs average power over the entire recording time (20ms).

Last segment spectrogram



Power Spectral Density of detected differential phase





Temporal domain representation of the detected differential phase for 3 segments along the FGB array.

Segment length = ΔL = 20m

$M = 26$

Conclusions

- The sparsity of Q-DAS temporal profile and a Pulse Compression technique were used.
- Mathematical rules for interrogation parameters given FBG array profile and system bandwidth were formulate. (For pulse-based & coded-based interrogation)
- PRR which is based only on the distance between adjacent reflectors was obtained thus breaking the relation between system total length to the standard maximum PRR.
- Scan rate of 5MHz was demonstrated for a system longer than 1km. Detection of ultrasonic acoustic waves of more than 100kHz was demonstrated.

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