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Executive Summary

European Space Agency
OSIP Open Channel
Early Technology Development
Activities Evaluation
Session 2020-03
Contract 4000132600 20NLGLC

Miniaturised distributed optical fibre sensors (DOFS) based on photonic integrated circuits (PICs) for space applications

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Acronyms

BOTDR: Brillouin Optical Time-Domain Reflectometry

DAS: Distributed Acoustic Sensor

DFB: Distributed Feedback

DOFS: Distributed Optical Fibre Sensor

EDFA: Erbium-doped fibre amplifier

ESA: Electrical Spectrum Analyser

OLO: Optical Local Oscillator

OSA: Optical Spectrum Analyser

PIC: Photonic Integrated Circuit.

PZT: Piezo-Electric Transducer

SOA: semiconductor optical amplifier

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1 Background

Distributed optical fibre sensors (DOFS) are highly suitable for monitoring temperature, vibration and strain using physical principles such as Raman, Rayleigh and Brillouin backscatter. They convert a standard telecom infrastructure to a sensor network providing thousands of virtual sensors per km using the intrinsic light/glass interaction during propagation.

DOFS have clear benefits in certain space applications, such as the ability to embed the sensors in the structure of reusable vehicles (even for ground testing, where they could remain after testing), the very small size of the sensors and simplified wiring). DOFS could also complement earth observations from space with ground or ocean-based monitoring, e.g., of ocean currents, salinity and temperature to improve climate models.

DOFS have wide terrestrial applications, such as the monitoring of energy cables including those linking offshore wind farms to the mainland. The terrestrial market is c. $100M with a typical annual growth rate of 5-10% per year including some applications that have 20+ years maturity.

The issue with present DOFS is that the interrogators (opto-electronic unit that probes the fibre and interprets the optical signal) consist of multiple optical components linked by fibre connections that need careful, bulky, packaging and are vibration-sensitive. This has, so far, rendered them unsuitable for space applications as well as certain ground-based applications.

2 Objectives and organisation of the project

The objectives of this project (Contract 400013260020NLGLC) were to investigate using Photonic Integrated Circuits (PICs) as the “optical engine” in DOFS with, potentially, strong benefits in size, cost, vibration tolerance and improved performance. The project also intended to demonstrate a single optical platform that can perform different types of DOFS measurement.

In the scope of the project, the PIC have a relatively limited functionality namely, to provide a frequency-shifting as well as an intensity-modulation function, which are fundamental functional blocks in DOFS. The basic principle of the frequency shifting is to injection-lock a first laser to an incoming light source and then to modulate the incoming light by gain-switching to create a frequency comb. One of the comb lines is then selected using injection-locking of a separate laser (demux laser) to the chosen comb line. The intensity-modulation function is implemented using a semiconductor optical amplifier (SOA) immediately prior to the PIC output.

The project was split into three phases, namely,

1. Procurement of the PIC, procurement of the packaging services for the PIC, procurement and assessment of dedicated electronics to control the PIC.
2. Functional test of the PIC with the control electronics
3. Optical system level testing

1. Phase 1

The specific objectives of the first reporting period (Phase 1) were:

1. To procure PICs for evaluation,
2. To demonstrate that the resulting devices can be packaged by commissioning a few of the devices to be packaged with fibre terminations and a suitable electrical interface,
3. To arrange for the manufacture of suitable, custom-designed electronics to control the PICs and to carry out functional testing prior to integrating the electronics with the packaged PIC,
4. To commission the design and manufacture of suitable enclosures for the PIC control electronics to allow the PIC and electronics assemblies to be tested safely.

PIC design and fabrication

Two variants of PICs to the specific requirements of the project were designed. The specific difference between the project needs and prior uses of similar technology is the requirement to lock the slave laser to an external source. A common external source allows multiple PICs to be driven together and therefore provide a *controlled relative frequency shift* between their outputs. In contrast, all the previous work on similar PIC technology had involved on-chip sources.

In addition, the DOFS application requires the ability to modulate the intensity of the light emerging from the demux laser; this was achieved by addition of a semiconductor optical amplifier (SOA) in the PIC [when unbiased, the SOA absorbs the light that is launched into it, whereas when forward biased, it amplifies the input light].

In the present application, the demands in terms of the spectral purity of the demux laser output are usually more challenging than in the applications that have been explored to date. Two variants were designed for the project, one a basic frequency-shifting element with intensity modulation and the second having a two-stage frequency selection. In the two-stage device, the intention was to provide a further level of filtering by locking a further laser to the first stage; this concept turned out not to provide any benefit.

These PICs are building blocks for demonstrating the concept of using PIC as the “optical engine” in a distributed sensor. It should be appreciated that several PICs will be required in each interrogator (Fig.1 illustrates the simplest case) and that they will need to be driven together in a synchronised manner. In this arrangement a probe forming branch and an optical local oscillator (OLO) branch each have independently controllable frequency shifts.

The intention had been to characterise the devices fully prior to packaging; however, the temperature stability of the probe test station was insufficient for that purpose. Nonetheless, at this point, the basic functionality of the devices was tentatively confirmed, including generating a comb and locking the demux laser to a selected comb line. The negatives from the testing were a limited rejection of adjacent comb lines (only 15 dB on the single demux device) and the central wavelength being off target by ~ 4 nm. The error on the operating wavelength was a constraint on further testing in that it forced the use of a narrow-line semiconductor laser, rather than a fibre laser as had been planned originally.

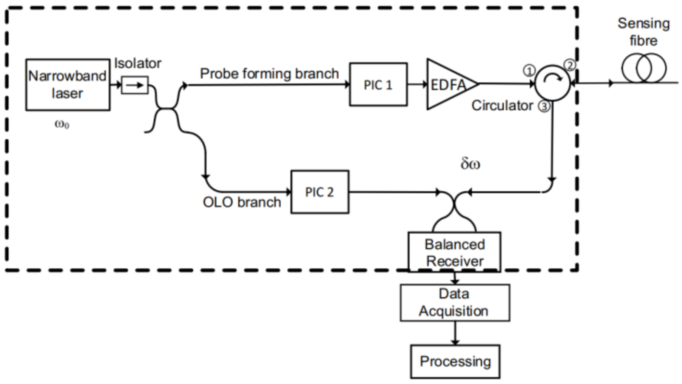

Figure 1: Example application of the PICs, which could be used for distributed vibration sensing or Brillouin OTDR (static temperature and strain) sensor, depending on the way in which the PICs are controlled.

Given that the testing facilities were not available to evaluate the PICs further in bare-die form, it was decided to proceed with packaging and re-visit the PIC testing on packaged devices.

PIC packaging.

The bare die PICs are unsuitable for testing in even a bench-top optical system. It was therefore necessary to achieve a basic level of packaging to ensure stable optical input and output in addition to the electrical connections, including several high-frequency electrical inputs.

The design of a prototype (non-hermetic) package for the devices and assembly of a few packaged devices was carried out by a separate company and completed in Phase 1. A photograph of one of the prototype devices is shown in Fig. 2.

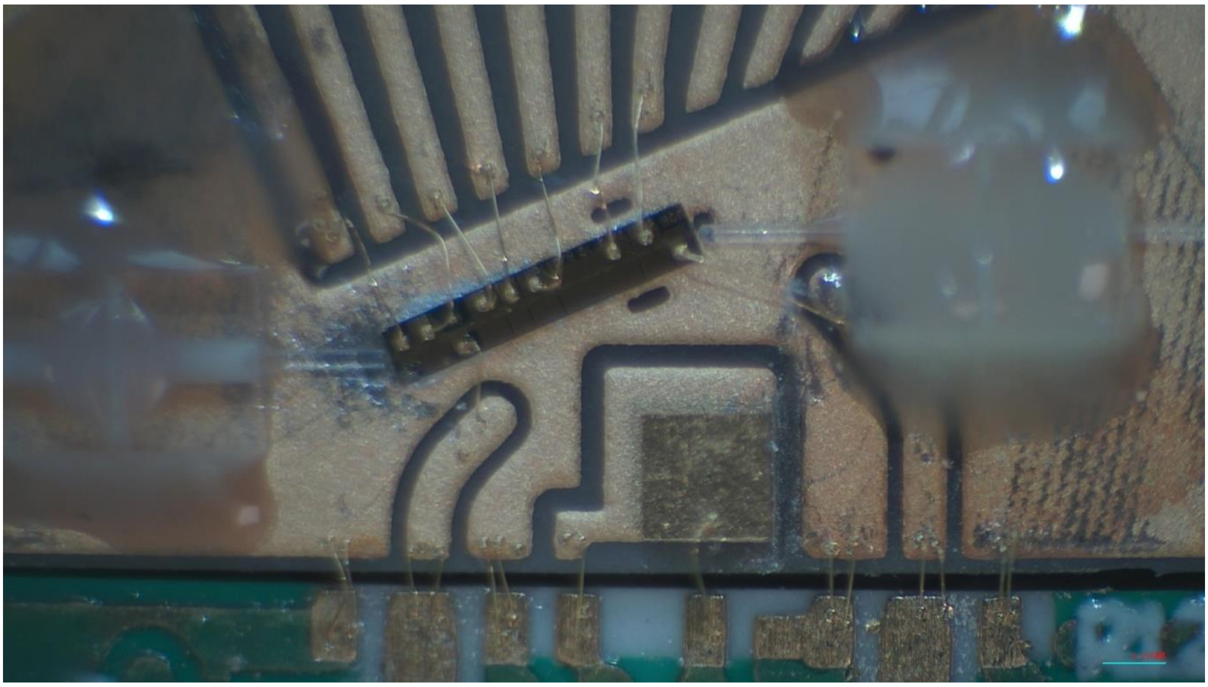

Figure 2: Photograph of a packaged PIC, attached to the ceramic sub-mount, wire-bonded and pigtailed.

Control electronics

Control electronics, able to adjust all the bias currents in the PIC, apply a controllable, agile, RF tone to one electrode and control the temperature of the PIC was designed, built, and tested. Purpose-mode housings were designed and constructed to mount and screen the electronics. The housing was also designed to remove the heat from the hot side of thermo-electric devices and from the most dissipative of the electronic components.

One critical requirement of the electronics is the ability to drive an SOA with fast edges so as to be able to generate short pulses if required. Fig. 3 shows a modulated output
(20 ns on/6.6 ns off/13.3 ns on) waveform, demonstrating edges faster than 2 ns at 10-90% points.

Figure 3: Oscilloscope trace of a current waveform generated by the control electronics (5 ns/div).

Another important function is the agile control of the frequency of RF (which, in a system will translate to the agile control of the frequency of the light passing through the device. Fig. 4 shows an example of a frequency-switched RF waveform centred at 2.13 GHz with various steps to illustrate the agility that was achieved, including a gap during which no RF is generated. The control electronics allows the frequency to be switched after a time as short as 13.33 ns and with a time resolution of 6.66 ns. The frequency setting resolution is better than 1 MHz with a theoretical range of ± 1000 MHz [in practice, the frequency range that the optical system can handle will be of order 500 MHz].

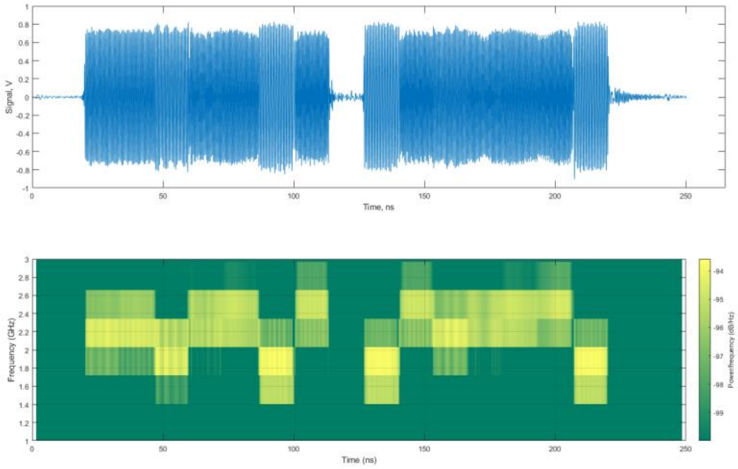

Figure 4: Example of a frequency-switched signal centred at 2.13 GHz and switched in various combinations at time steps of 13.33 ns. Upper plot: time domain signal; lower plot: spectrogram of the time domain signal.

The conclusions of Phase 1 were that the objectives of building and packaging prototype PICs for the DFOS proof of concept, as well as the associated control electronics had been met.

2. Phase 2

In Phase 2, the behaviour of the PIC (as fabricated and packaged in Phase 1) and controlled by the electronics (built and evaluated in Phase 1) was assessed.

Intensity modulation

The intensity is modulated by means of an SOA. An example of such a modulation is shown in Fig. 5 which demonstrates a pulse duration of 7 ns (full width at half-maximum), sufficient for a spatial resolution below 1 m. However, the extinction ratio, at 50:1, is insufficient for the needs of DOFS, where the requirement is of order 10^4-10^5:1 (depending on the pulse duration and measurement range that are required).

Figure 5: Intensity modulated output of the PIC

Comb formation and line selection.

The ability to modulate the light injected into the PIC and to form a comb was evaluated and it was confirmed that, under selected conditions, at least three pairs of sidebands at power levels with 5 dB of the incoming light.

The second step of locking the demux laser to a comb line was also achieved, as illustrated in Fig. 6.

However, extensive testing using a wide range of parameters resulted in only limited selectivity. At best, the experiments achieved only 11.5 dB for the selected line, relative to the nearest unwanted frequency.

The conclusion of the Phase 2 was therefore that the basic principles on which the PIC was based were demonstrated but, however, that the performance achieved on two important criteria were inadequate.

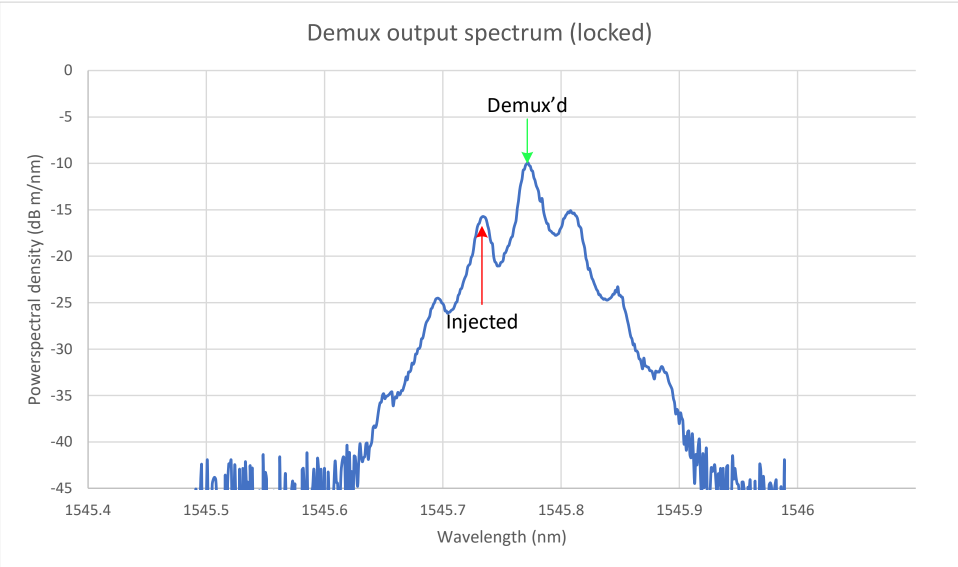

Figure 6: Example demultiplexed comb line.

3. Phase 3

It was believed that the main reasons for the shortfall in performance were in the fabrication of the PIC and this could not be recovered without a new PIC device, which would have been well outside the timescale and costs of the project. It was therefore agreed with the Technical Officer that the principles would be demonstrated by assembling a breadboard of the PIC using external discrete components (packaged semiconductor lasers, pigtailed comb sources).

This activity was carried out in Phase 3, resulting in the demonstration of a fast Brillouin optical time domain reflectometry (BOTDR) measurement (which is sensitive to temperature and strain) and of a distributed acoustic sensing (DAS) measurement (dynamic strain).

As an example, a BOTDR measurement of the frequency shift in a strained section of a test fibre is shown in Fig. 7. The strain applied to the fibre was modulated with a dynamic strain of up to 0.3%.

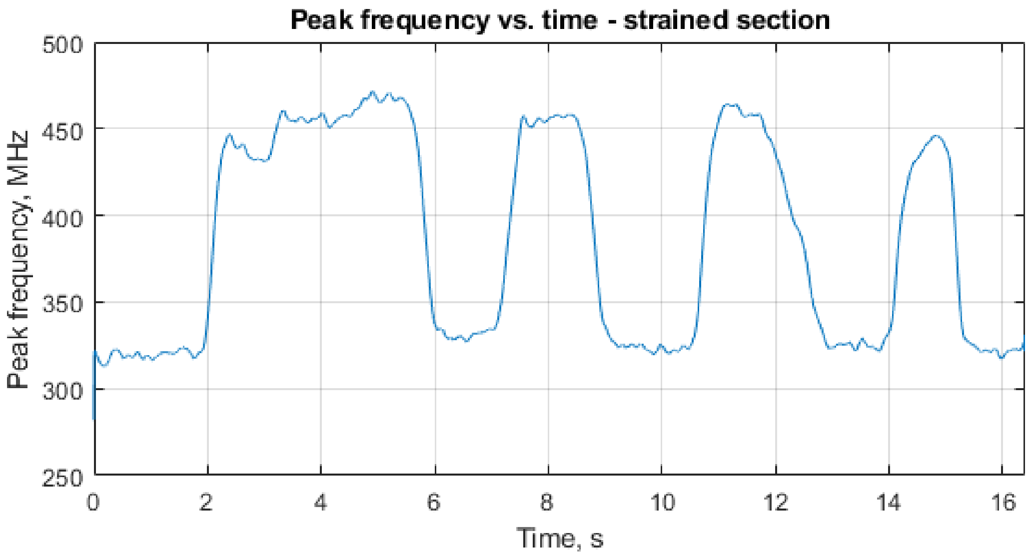

Figure 7: Fast quasi-static strain measurement based on Brillouin OTDR (the frequency axis is offset by 10 500 MHz)

The data was acquired at a pulse repetition frequency of 1 kHz but smoothed over 100 acquisitions to give dynamic response time of 100 ms.

A repeatability of the Brillouin frequency of 1.66 MHz for an acquisition time of 0.1 s was demonstrated, equivalent to a temperature resolution of 1.6 K or a strain of 33 $\mu\varepsilon$.

By re-arranging the frequency shifts in the OLO, the same optical arrangement was adjusted to make multi-frequency DAS measurements. Thus, the sensing fibre was probed simultaneously at 5 frequencies offset from the OLO from 100 to 300 MHz in 50 MHz steps.

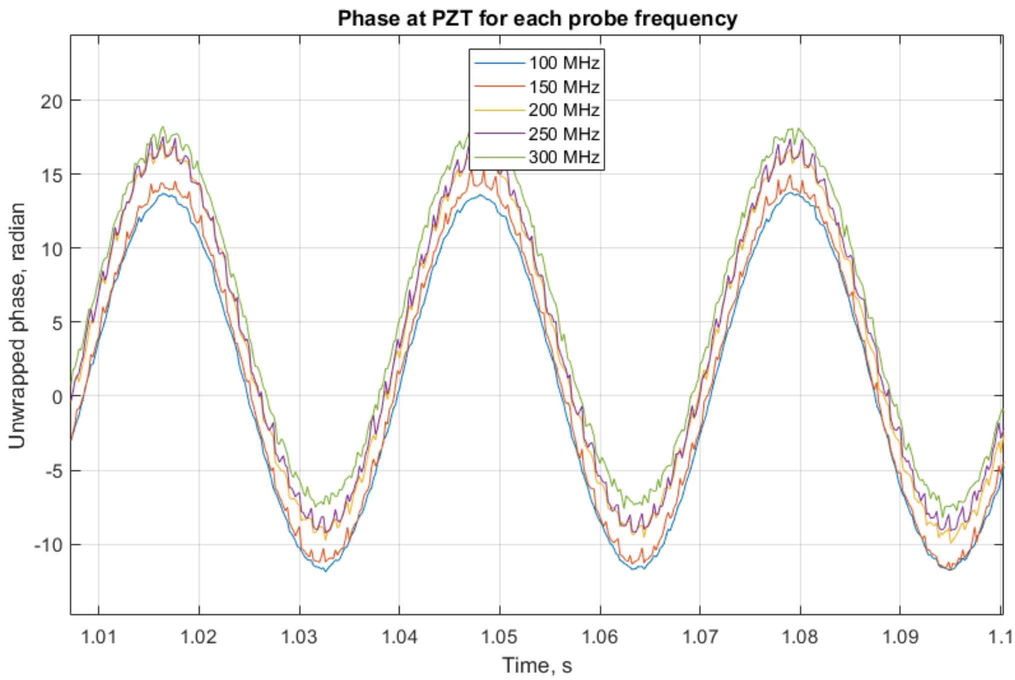

Figure 8: Multi-frequency dynamic strain measurement using the optical breadboard in DAS mode.

An example of the dynamic strain measured at a piezo-electric transducer (PZT) is illustrated in Fig. 5 where 5 measurements of the signal applied to the PZT were acquired simultaneously. It is usual practice to aggregate results such as those shown in Fig. 8 to provide an optimised result which avoids the effects of fading.

3 Conclusions

The basic principles of integrating the key optical functions required for a distributed optical fibre sensor onto a PIC were demonstrated.

However, the performance criteria required for applying this concept were not met owing to deficiencies in the fabrication (and possibly design) of the specific PIC devices manufactured for the contract.

A demonstration system using discrete devices was therefore assembled and used to validate the measurement concepts. The results provide confidence that a correctly designed and manufactured PIC could achieve the objectives of the contract, namely, to integrate the main optical functions of a DOFS onto an integrated optical device.