Sensors and photonic integration

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Abstract. *Photonic integration will become more and more a dominant factor for successful economic deployment of optical sensors, enabling a fast growing number of applications. Because the present sensors employ many discrete photonic and opto-electronic components, development of sensor-dedicated devices and photonic integrated circuits is now the required next step to fuel many new applications.*

Photonic integration for sensors: benefiting from telecom achievements

In analogy to the application of Photonic Integrated Circuits (PICs) for ultra-high capacity telecommunications networks, the role of photonic integration becomes more and more a decisive factor for the economic implementation of sensors. The telecom-drive for cost-effective realization of complex photonic and opto-electronic circuits is now even more urgently required to spur the development of photonic sensors. At the same time, specific requirements for sensors can initiate PIC-oriented research that will enable realization of novel telecom devices and complex circuits as well.

Challenges and opportunities for photonic integration

Photonic integration will benefit a great number of applications in the field of photonics-based sensing [1]. Figure 1 indicates only two out of many basic sensor configurations and lists some specific features of sensor-oriented PICs.

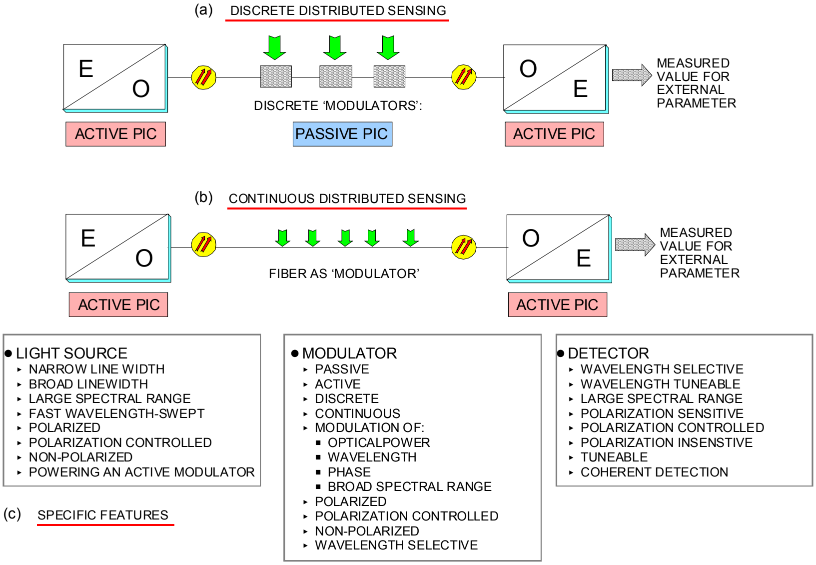

Fig. 1: Sensor configurations employing: (a) passive- and (b) active PICs, (c) some specific features for sensor-oriented PICs

Dedicated functionality in (low-cost) photonic integrated circuits will enable many novel applications for sensors, similar to the way micro-electronics has changed society in many ways. Worldwide, novel sensor concepts are designed, being the response to measure an ever increasing number of phenomena on a more and more accurate scale. Applications range from e.g. structural integrity monitoring to security to process control to medical biophotonics. Frequently these novel sensor concepts require advanced photonic excitation – and analysis techniques to resolve the parameters of interest. Also, ongoing developments in the field of e.g. micro structured fibers and photonic crystals offering advanced photonic effects for sensing will require precise excitation and complex read-out techniques. Presently, one is usually pressed to realize such complex functionalities using many separate photonic- and opto-electronic components. PICs offering equivalent or better performance at attractive costs will therefore serve as an *enabling technology* for novel sensors. Small volume, low mass, vibration-immunity, increased performance and high-reliability are key factors for high-tech applications in e.g. aerospace and automotive industry. Active PICs can be used as advanced light sources and detectors connected to e.g. passive 'modulators' (being PIC-based or otherwise) or as 'active' sensing platforms. Optically powered sensors shown in Figure 2 will expand their applications by PIC-based ultra low power lasers and sensing circuits.

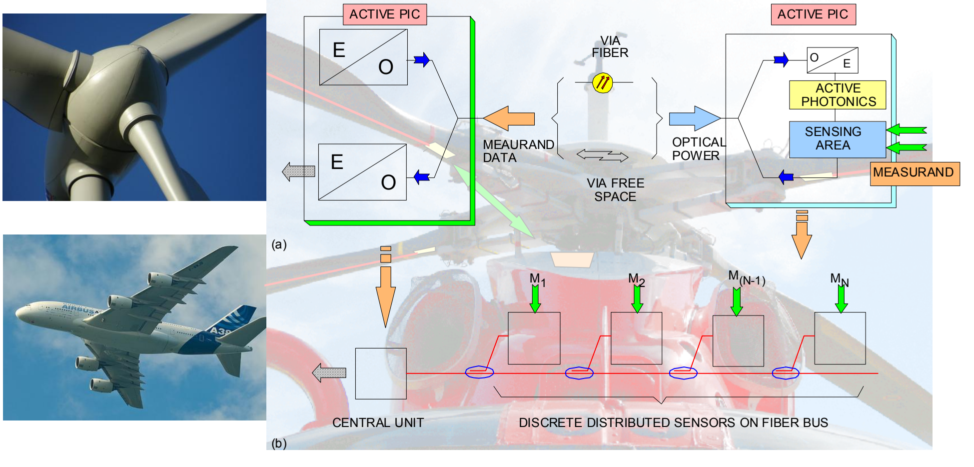

Fig.2: PIC-based opto-powered sensing: (a) basic configuration, (b) bus structure. Background: application of free-space sensors for helicopter rotor blade monitoring

Depending on sensing area design, an active PIC can responds to (multiple) physical and chemical parameters, transmitting encoded measurand-data back to the opto-powering unit. For example, an active PIC employing an interferometer with a chemo-optical transduction layer on top of its sensing-waveguide responds to a specific chemical parameter, while electro-optic effects in the waveguide will respond to electrical parameters. The sensing-PIC can be powered via fiber or free space, the latter enabling applications requiring wireless operation of the sensing-PIC, as in wind turbines, airplane propellers or rotor blades of helicopters. Such applications require however receivers and transmitters being optimized for free-space optical communication. A challenge will be to keep their related power consumption within requirements.

Application: Continuous distributed sensing of strain and temperature

Distributed sensing of strain and temperature becomes increasingly important for e.g. structural health monitoring and economic optimization of e.g. bridges, quay walls, wind turbine blades, large-area roofs and high-power (intercontinental) electrical power cables. Such applications require large objects to be monitored at multiple spots, urging low costs for sensors, cabling and installation. Presently, distributed strain and temperature are mostly monitored using a telecom optical fiber as sensor, being reinforced and embedded into the object or attached to its outside. Spatial-resolved monitoring of strain is based on analysis of the Brillouin shift of a backscattered light pulse while traveling along the fiber, as shown in Figure 3.

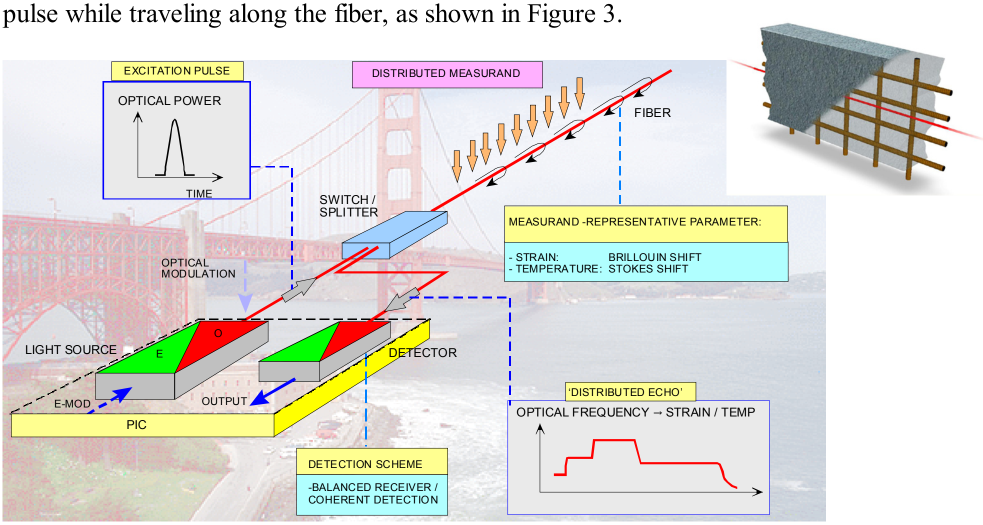

Fig. 3: Distributed sensing of strain and temperature using an optical fiber as sensor

Temperature measurement is based on analysis of time-resolved Raman scattering. A strain of 1% in a telecom grade fiber introduces a frequency shift of about 497 MHz. Resolving a much-wanted strain detection limit of 1 microstrain requires to detect a frequency change of 49.7 kHz at a power level that is about 10^5 times lower than that of the excitation pulse. In addition, a spatial resolution of e.g. 0.2 m requires the strain-induced frequency deviations to be measured within 1 ns. Commercial systems for distributed strain are specified at 20 microstrain detection and 0.4 m spatial resolution for a price of about k€100. PIC-based instruments are targeted at 10-15 % of this price

Application: A Neutrino telescope using discrete distributed sensors

The KM3NeT ('Cubic Kilometer Neutrino Telescope') [2] as under design by Nikhef and an international collaboration of scientific institutes, is deep-water neutrino detector to be operating at a seabed at 3-5 km depth (Fig. 4). High-energy astrophysical neutrinos are elementary particles with zero charge and very low mass. After traveling through the Earth they can interact with sea water, creating a muon traveling at a speed higher than the speed of light in the sea water. Under this condition, the slowing-down muon emits the characteristic blue-colored Cherenkov radiation along its track. KM3NeT will detect this radiation using some 10.000 Optical Modules, being glass spheres of 400 mm diameter, each containing up to 32 photomultiplier tubes (PMTs). Digital PMT-data must be real-time transmitted to the shore station for Cherenkov-track reconstruction, requiring a 1ns on-shore timing accuracy of a photon hit. Data will be transmitted over up to 100 km via submarine electro-optical cable containing up to 100 fibers each carrying 100 DWDM channels at 0.4 nm spacing. Total data rate to the shore station will be 10.000 x 10 Gb/s, or 100 Tbit/s. Specific PICs for KM3NeT, and distributed sensor networks in general, are multi-wavelength laser arrays, E/O data interfaces, all-optical serializing/de-serializing and data processing in the photonic domain.

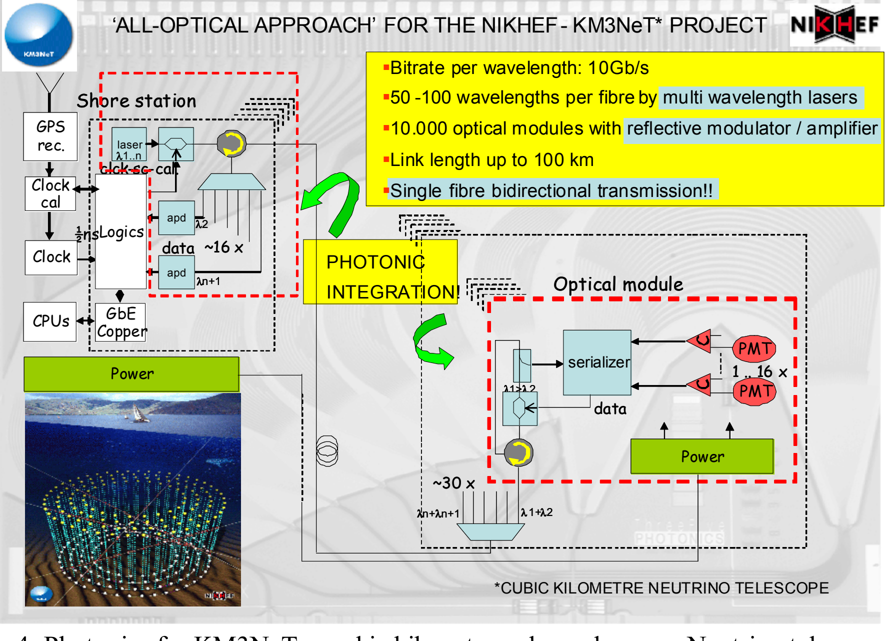

Fig. 4: Photonics for KM3NeT: a cubic kilometer volume deep-sea Neutrino telescope

Closing remarks

Apart from applications in telecom, passive and active PICs will, more than ever, enable to expand the number of applications of photonic sensors. PICs will spur development of novel sensors and advanced photonic techniques for sensor excitation and readout. Also, the synthesis between complex functionalities offered by PICs and photonic effects in e.g. micro structured fibers and photonic crystals will enable sensors being capable to measure multi-parameter phenomena simultaneously. Dedicated PICs will also contribute decisively to the success of scientific programs in the field of fundamental research, where massive collection of vast amounts of data from thousands of distributed signal sources is crucial for progress in e.g. fundamental sciences. Governmental rules on safety, liability and insurance regulations will act as a very efficient catalyst to accelerate the development and expansion of novel types of photonic sensors.

References

[1] J.M. López-Higuera, Handbook of Optical Fibre Sensing Technology, John Wiley and Sons, LTD, 2002, ISBN 0-471 82053 9.

[2] KM3NeT Neutrino Telescope: www.km3net.org , www.nikhef.nl.