Photonic sensors for hypersonic vehicle guidance/control and structural health monitoring

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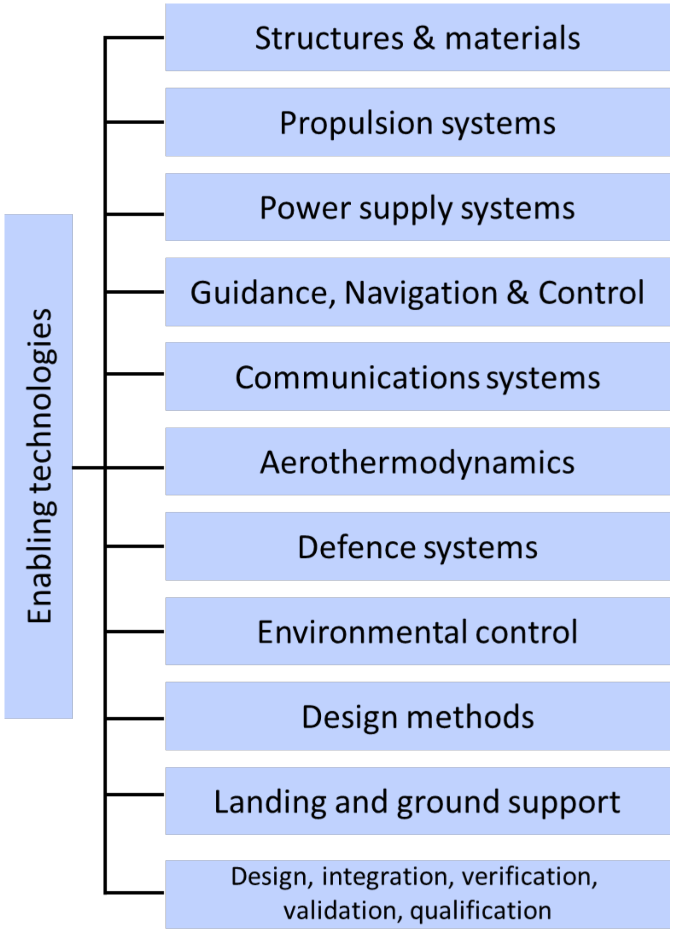
Hypersonic vehicles

Hypersonic vehicles work at extreme operation conditions of speed (Mach > 4-5) and altitude (of the order of tens of Km) where some thermal and chemical phenomena require the use of dedicated technologies.



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In progress

Examples of critical issues

- An hypersonic vehicle typically suffers from extreme temperature/pressure gradients and strong shocks.

Structures and Materials

- Autonomous navigation is a fundamental function in almost all vehicles.
  The hearth of an autonomous navigation system is the inertial unit, whose task is the calculation of position, velocity and attitude through the data provided by inertial sensors.

Guidance, Navigation and Control

Need of sensing technologies with high accuracy and immunity to external disturbances (Ex.: Space X, Falcon 9 FOG (resolution ~ 1 °/h))

Why Photonics?

Photonics deals with generation, processing, and detection of light

It is a key enabling technology

which has demonstrated its potential in many application fields, e.g. telecommunications, energy, lightening, environmental monitoring, robotics, industrial production, biomedicine, medical imaging, displays, homeland security, aerospace, and defense.

Main advantages: higher efficiency, lower losses, lower power consumption and smaller size.

Some *additional benefits for aerospace applications* are volume and mass reduction, reduced losses, higher integration level, better electromagnetic compatibility, down-link reduction and on-board data processing.

Photonics in Space

In recent years, photonic sub-systems for the transportation segment and the ground segment have been already developed but most of the interest for the photonic technologies is addressed towards the space segment, i.e. payloads and satellite platforms.

Well-established applications:

- Optoelectronic gyros (He-Ne RLG and FOG);
- Star tracker and Sun sensor;
- Solar cells for satellites power supply;
- Optical payloads for EO and in situ analysis.

Emerging applications:

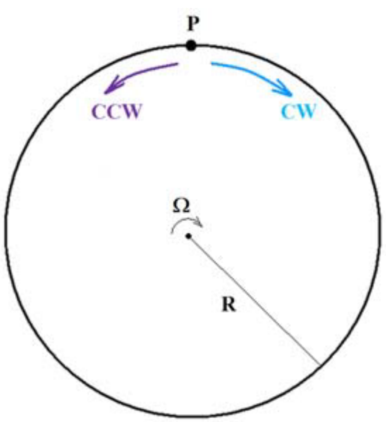
- Photonic integrated circuits for RF signal generation/processing;
- Fiber links for on-board data transfer;
- Lasercom technology;
- Photonic sensing.

Gyroscopes

Gyroscopes are the most critical and costly components in an inertial measurement unit.

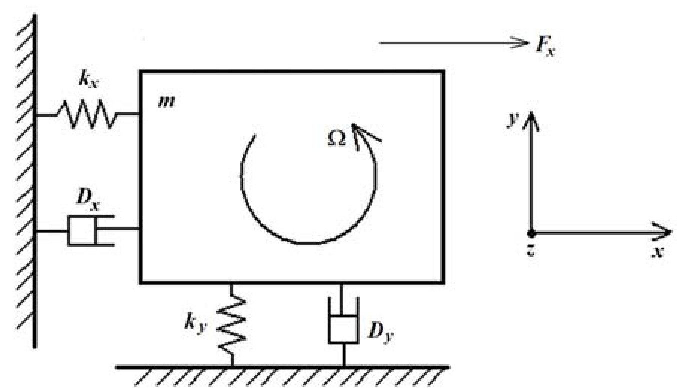
The main gyro performance parameters are:
Resolution: minimum detectable angular velocity
Bias drift: non-zero output when the sensor does not rotate
Angle random walk: noise contribution with a variance linearly increasing as time increases

Physical effects



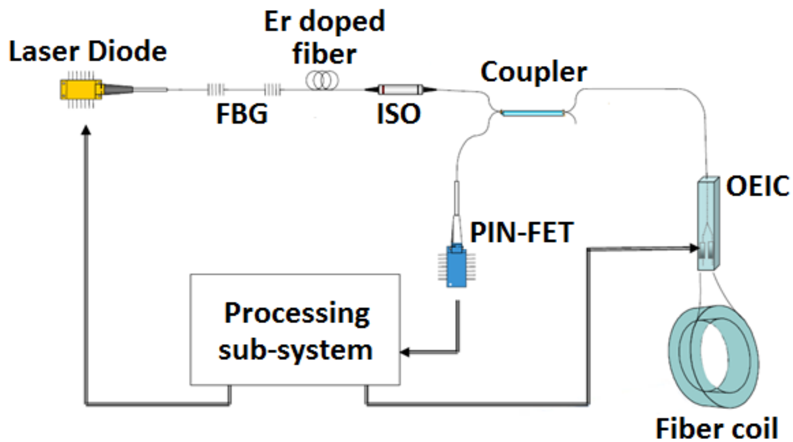
Sagnac Effect

Coriolis Effect

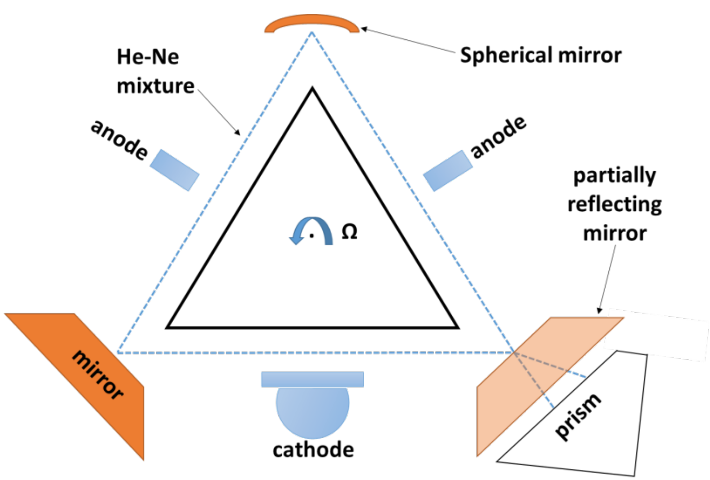


Commercial high performance optoelectronic gyroscopes

Fiber Optic Gyro



He- Ne Ring Laser Gyro



Weight > 4 Kg

Volume > 1000 cm^3

Power consumption > 10 W

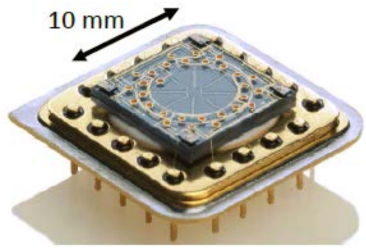
Bias drift < 0.01°/h

ARW < 0.001 °/√h

Resolution < 0.1 °/h

Bulk sensors

Gyros miniaturization through MEMS technology



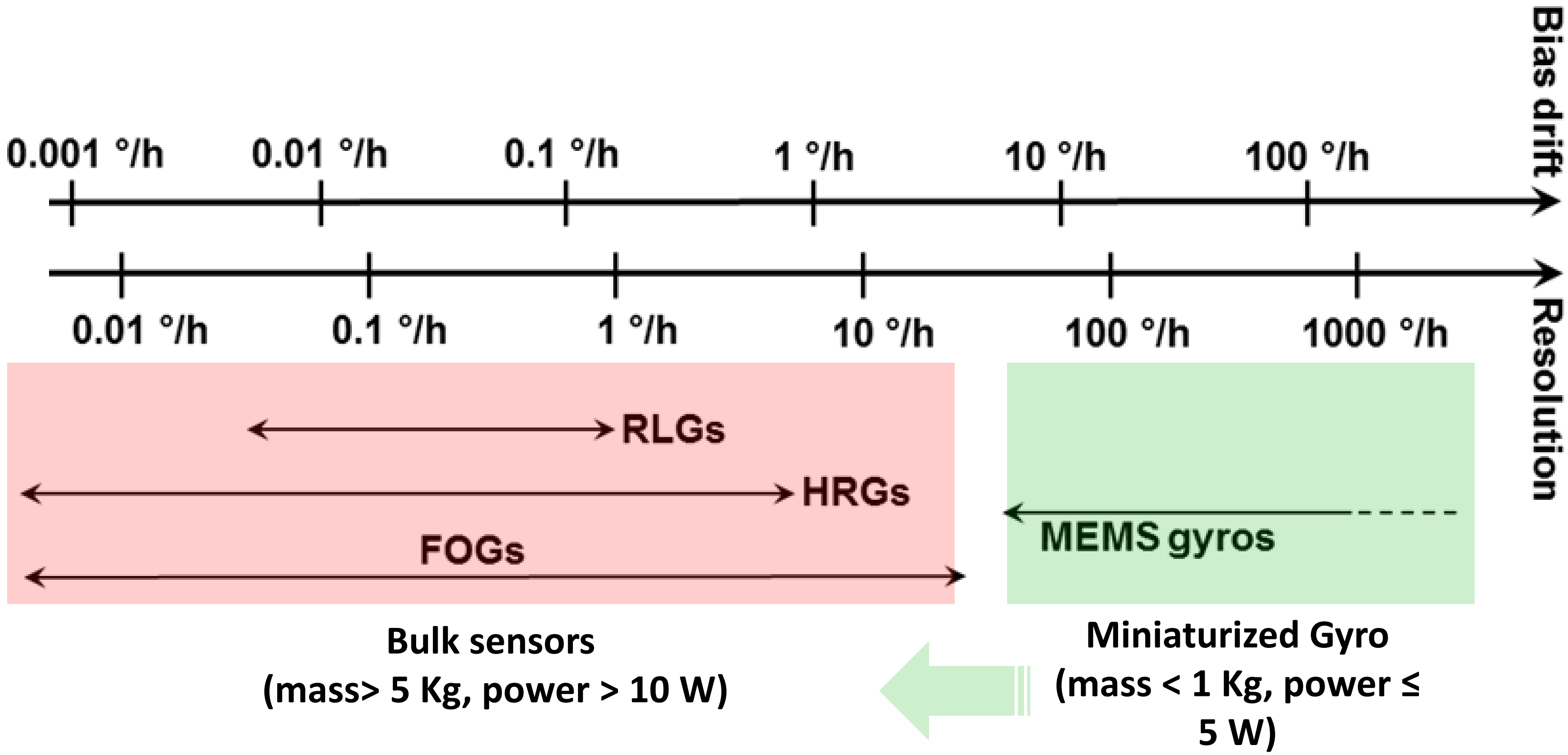
Requirement	Specified	Measured on EQM	
ARW – Angular Random Walk	0.24 deg/√h	0.009 deg/√h	
RBD – Bias over temperature	10 deg/h	40 deg/h (FPGA) 10 deg/h (ASIC)	
SSC – Switch on to Switch ON (*after power cycling*)	10 deg/h	2 deg/h	
Angular Rate Bias	10 deg/h	Max constant drift of 0.1 deg/h/day Periodic bi-annual calibration allows to remain within the spec	
Scale Factor Linearity	< 5000 ppm	< 1000 ppm	
Resolution/LSB	0.27 arcsec/s	0.27 arcsec/s	
Shocks	1500 g	1000 g passed 1500 g survived but bias change	
Random Vibrations	25.1 g rms	25 g rms survived but bias change	
Temperature range (Qual)	-40° to +70° C	-40° to +60° C (FPGA) -40° to +70° C (ASIC)	

750g

5 W power supply

S. Kowaltschek, “Lessons learnt from the SiREUS MEMS detector evaluation,” 6th ESA Workshop on Avionics Data, Control and Software Systems, 2012.

Integrated optoelectronic gyros: motivations



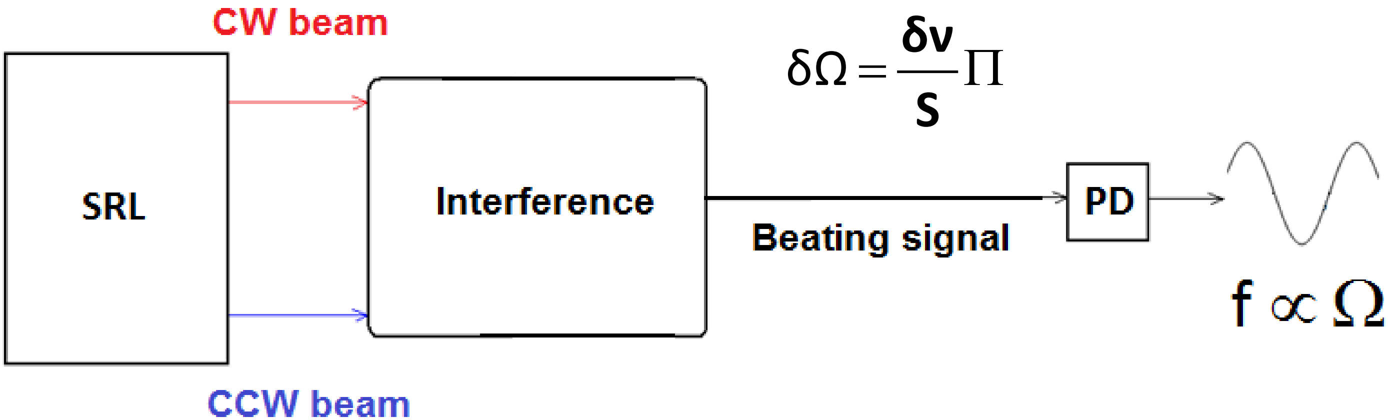
<u>Technological challenge</u>: **miniaturized gyroscope with resolution < 50 °/h.**

1. new generation MEMS gyros for Space.
2. both interferometric and resonant (active/passive) integrated optoelectronic gyros.

F. Dell'Olio et al., "Recent advances in miniaturized optoelectronic gyroscopes," J. Europ. Opt. Soc. Rap. Public., 2014.

Gyros miniaturization through integrated optics

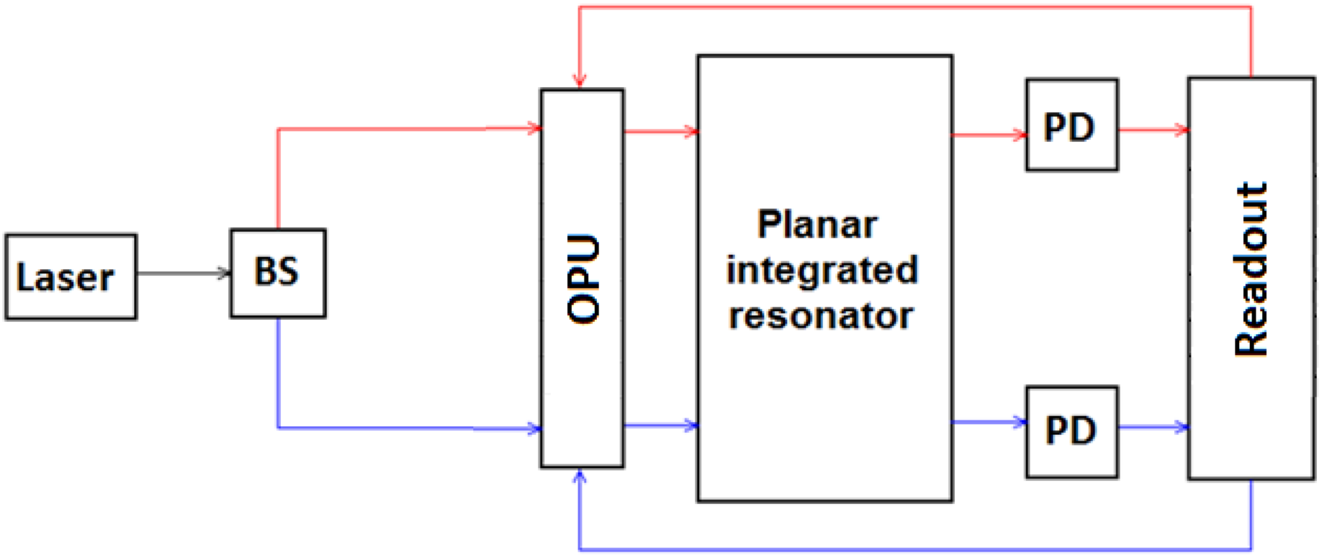
Active configuration based on the SRL



$$\delta\Omega = \frac{\delta\nu}{S}\Pi$$

$$f \propto \Omega$$

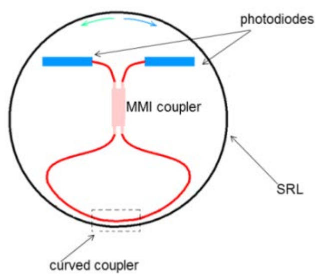
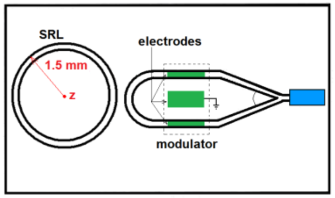
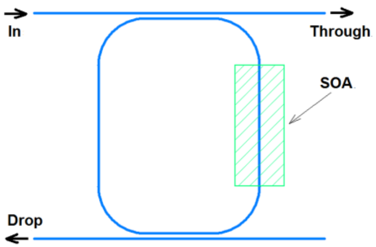
Passive configuration based on the planar ring resonator



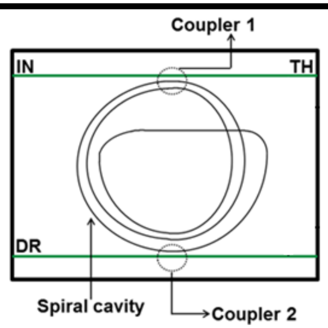
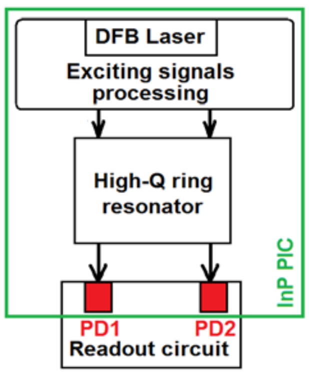
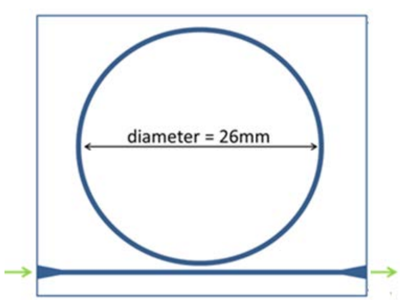
C. Ciminelli, F. Dell'Olio, C. E. Campanella, M. N. Armenise, "Photonic technologies for angular velocity sensing", Advances in Optics and Photonics, Vol. 2, 370-404 , 2010.

$$\delta\Omega = \frac{\sqrt{2}}{S \times Q}\nu_0\Pi$$

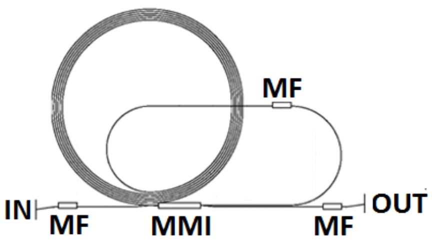
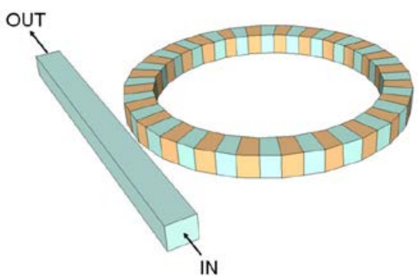
Summary on the Lab activities on integrated optoelectronic gyros

Years	Configuration	Description	Results	Publications/patents	Funding
1996-1998		Design of a novel gyroscope configuration based on the monolithic integration of the rotation-sensitive semiconductor ring laser and the readout circuit.	Theoretically estimated resolution about 300 °/h.	M. Armenise, P. J. R. Laybourn, Proc. SPIE, vol. 3464, pp. 81-90, 1998.	—
1999-2002		Detailed design of a patented gyroscope configuration including a MQW ring laser and an innovative readout circuit.	Theoretically estimated resolution about 0.01 °/h. Clear identification of the quantum effects limiting the sensor performance. Critical aspects: lock-in effects and mode competition.	M. N. Armenise et al., J. Lightwave Technol., vol. 19, n. 10, pp. 1476-1494, 2001. M. N. Armenise, et al., European patent EP1219926 (Filed Nov. 2000).	TRP IOLG ESA project ESA/ESTEC-MI CONTRACT n. 16782/02/NL/PA.
2003-2006		Theoretical/experimental research activity on a gyroscope based on a Semiconductor Optical Amplifier(SOA)-compensated ring resonator.	Fabrication of a silica spiral resonator including a InP-based SOA. Nonlinear effects occurring in the SOA limit the possibility of appropriately controlling the device.	C. Ciminelli, et al., Proc. SPIE, vol. 5728, pp. 93 - 100, 2005.	TRP IOLG ESA project ESA/ESTEC-MI CONTRACT n. 16782/02/NL/PA.

Summary on the Lab activities on integrated optoelectronic gyros

Years	Configuration	Description	Results	Publications/patents	Funding
2004-2012		Design, fabrication, optical characterization of a Resonant Micro Optical Gyro (RMOG) based on a spiral resonator in silica-on-silicon technology.	Theoretically estimated resolution about **5 °/h**.	C. Ciminelli, et al., IEEE Photonics J., vol. 4, pp. 1844 - 1854, 2012. C. Ciminelli, et al., DGaO/SIOF Joint Meeting Brescia, June 2009.	TRP IOLG ESA project ESA/ESTEC-MI CONTRACT n. 16782/02/NL/PA.
2007-2010		Design of a fully integrated gyroscope. Selected technology: InP-based Photonic Integrated Circuits (PICs).	Theoretical demonstration of the feasibility of a gyro-on-a-chip (GoC) with resolution of **10 °/h**.	F. Dell'Olio, et al., 1st Networking/Partnering Day 2010, Noordwijk, Jan. 2010. http://www.congrex.nl/10c07.	NPI PhD funded by the ESA/ESTEC-PoliBA Cooperation Agreement n. 20199/06/NL/PA.
2011-2013		Design, fabrication, optical characterization of the gyro sensing element with the development of the sensor readout electronic board.	Demonstration of an InP-based ring resonator with Q = 10^6 (ten times greater than the state-of-the-art). Resolution of **10 °/h**.	C. Ciminelli, et al., Optics Express, vol. 21, n. 1, pp. 556-564, 2013.	TRP MiOS ESA project 4000102311/10/NL/PA.

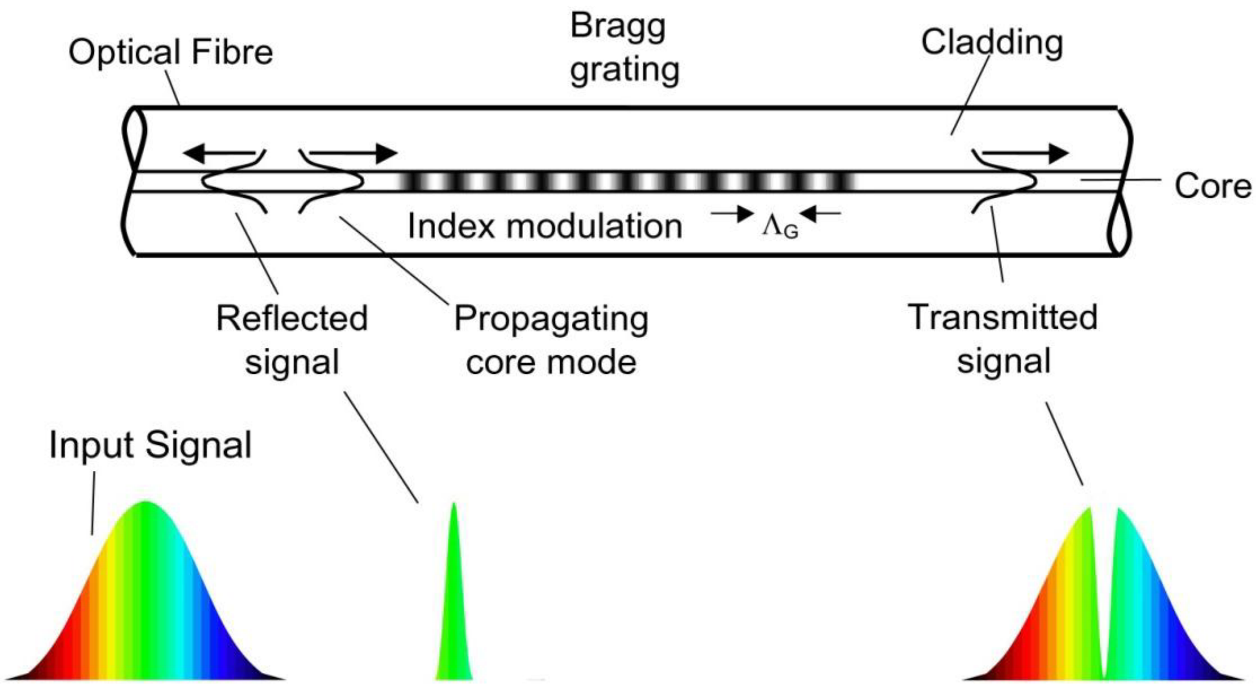
Summary on the Lab activities on integrated optoelectronic gyros

Years	Configuration	Description	Results	Publications/patents	Funding
2014-2015		Design, fabrication, optical characterization of a InP ring resonator intended for gyro application fully compatible with the COBRA platform.	Demonstration of a InP-based ring resonators with Q of the order of 10^5 - 10^6 easily integrable with the other gyro components Resolution of **10 °/h**.	C. Ciminelli, et al., IEEE Photonics J., vol. 8, 6800418, 2016. D. D'Agostino, et al., Opt. Express, vol. 23, pp. 25143–25157, 2015.	Scientific collaboration PoliBA- TU/e.
2013-2016 (ongoing)		Detailed design the 1PhC ring resonator. Selected technology: Si_xN_y	Theoretically estimated resolution about **0.01 °/h**.	C. Ciminelli, et al., "Optical Rotation sensor as well as method of manufacturing an optical rotation sensor", European Patent n. EP 056933 C. Ciminelli et al., ICTON 2016. Invited paper. .	MICAD project ESA/ESTEC-PoliBA Contract n. 5401000410/0/0/0/0. NPI PhD funded by the ESA/ESTEC-PoliBA Cooperation Agreement n. 367 – 2014

Lesson learnt so far on photonic gyros

- Photonics gyros are able to cover a performance range from tactical to inertial grade.
- Commercial optical gyros are immune to e.m. interferences and to mechanical issues, as already demonstrated by their use in civil and military vehicles (e.g. satellites, airplanes, missiles, submarines) and in launchers.
- Integrated-optics technologies can reduce the size of the angular velocity sensors, preserving the achievement of potential high performance (resolution < 1 °/h).
- Additional investigation on the tolerances to the radiations and on the repeatability of the fabrication processes involved is needed.
- What else to get a gyro? Development of an integrated read-out electronics, together with specific control algorithms and data handling software. Proper mechanical design of the gyro unit to house all optical and electronic elements. Flight test.

Fiber Bragg Grating (FBG)



$$\lambda_B = 2n_{eff}\Lambda_B$$

Local deformation and/or local temperature change ⇨ grating period variation ⇨ changes of the reflected wavelengths

Fiber Bragg Grating (FBG) – key features

- FBG is a successful technology, largely used in telecommunications and sensing applications.

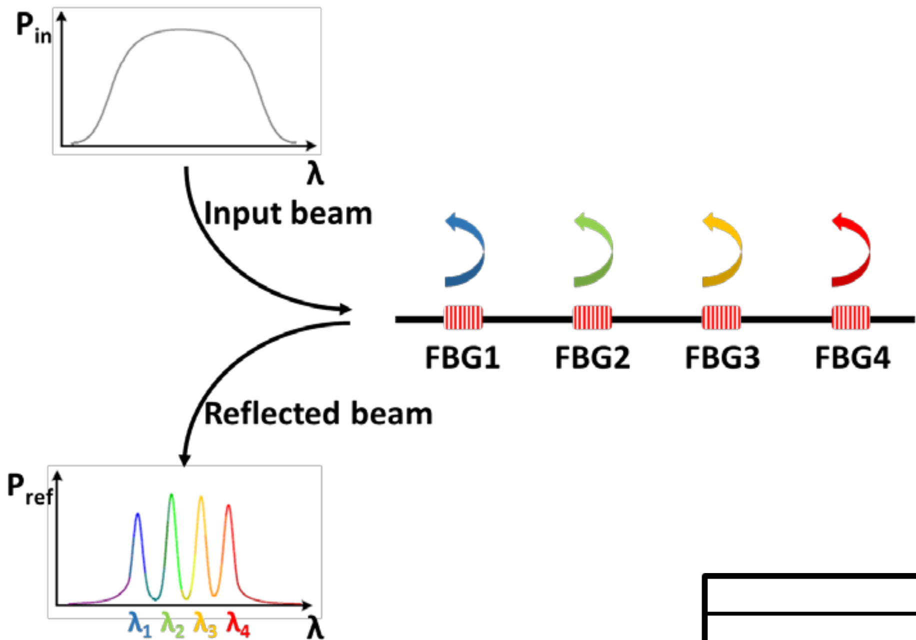
- FBGs have the general advantages of the optical fibres: they are light, small (*like hair*), flexible, wideband, immune to e.m. interferences.

- A single fibre can carry information from thousand of FBG sensors, providing large numbers of measurement points with a very reduced total weight of the whole sensing system.

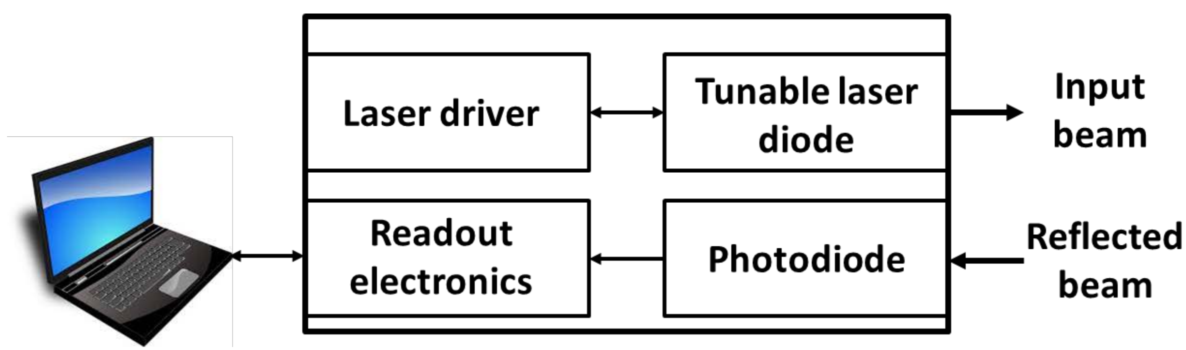
Multiplexed FBG sensing

Several FBG sensors with different grating periods can be inscribed along the same fiber to sense temperature or strain at a number of points.

In FBG sensors, the grating is excited either by a tunable laser or a broadband light source.



Block diagram of an interrogator based on a tunable laser diode



FBG in hypersonic vehicles

FBG networks can improve structural and system efficiency in space vehicles by

- reducing data system integration time and cost
- providing validated structural design data
- increasing capability of measuring multiple parameters in real time (strain, temperature, liquid level, shape, etc.)
- providing continuous real-time structural health monitoring in spacecraft during the mission life cycle

Conclusions

- The development of new hypersonic vehicles for both civil and military purposes requires effective and very innovative solutions to many technical problems. The challenging operating condition of hypersonic vehicles requires the use of **sensing technologies with high accuracy and immunity to external disturbances**. The basic features of **photonic sensors** match very well with such requirements.
- Some **recent advances in the field of photonic sensors for inertial navigation and structural health monitoring** have been discussed, with an emphasis on the features of these devices that can be useful in the **context of hypersonic flight**.
- **Theoretical/experimental activity** is required to develop the above-mentioned technologies and to asses their specific applications in the field of hypersonic flight.

Optoelectronics Lab - Selected publications on gyros and FBGs

- M. N. Armenise, et al., "Integrated optoelectronic angular velocity sensor," European patent n. EP1219926, 2000.
- M. N. Armenise, et al., "Modeling and Design of a Novel Miniaturized Integrated optoelectronic Sensor for Gyroscope Systems," J. Lightwave Technol., 2001.
- M. N. Armenise, et al., "Optical fiber Bragg gratings. Part I. Modeling of infinitely long gratings," J. Opt. Soc. Am. A, 2002
- M. N. Armenise, et al., "Optical fiber Bragg gratings. Part II. Modeling of finite-length gratings and grating arrays," J. Opt. Soc. Am. A 2002.
- C. Ciminelli, et al., "A new integrated optoelectronic angular velocity sensor," Proc. SPIE, 2005.
- M. N. Armenise, et al., *Advances in gyroscope technologies*, Springer, 2011.
- C. Ciminelli, et al., "High-Q Spiral Resonator for optoelectronic Gyroscope Applications: Numerical and Experimental Investigation," IEEE Photonics Journal 2012.
- C. Ciminelli, et al., "High performance InP ring resonator for new generation monolithically integrated optoelectronic gyroscopes," Optics Express, 2013.
- C. Ciminelli, et al., "Optical Rotation sensor as well as method of manufacturing an optical rotation sensor", European Patent n. EP 056933, 2013.
- C. Ciminelli, et al., "A high-Q InP resonant angular velocity sensor for a monolithically integrated optoelectronic gyroscope," IEEE Photonics J., 2016.
- C. Ciminelli, et al., *Advanced Photonic Devices and Systems*, World Scientific, 2016.