SOI Sensors in Extreme Environments

Shangjiong Yang[1], Kirk Green[2], Mirvais Yousefi[1]

[1]TNO Science and Industry, P.O. Box 155, 2600AD Delft, The Netherlands
[2]TNO Bouw en Ondergrond, P.O. Box 49, 2600AA Delft, The Netherlands

At TNO, we focus on the applications of integrated nanophotonics (INP). Figure 1 shows an example of TNO INP ring resonators. We characterize the physical, mechanical, optical, and chemical reliability of the devices, which is essential for use in industrial realities.

Introduction

Industry strongly favors photonic solutions on nanodimensions, anticipating advanced nanophotonic devices in, for example, telecommunication or sensing. The reason is that integrated nanophotonics offers high price-sensitivity ratio, CMOS compatible production, and a shrinking gap to low-price (disposable) devices. Nanoscaled photonics can encourage light-matter interaction by orders of magnitude. At TNO, we focus on the INP sensing devices and investigate the physics and applications of nanophotonic structures. In particular, we are interested in light confining structures that can slow down, enhance and manipulate light. In this fashion, it enables the optical properties of devices to be controlled externally, either by an optical or electro-optical means. Figure 1 shows an example of TNO INP ring resonators. In this work, we characterize the physical, mechanical, optical, and chemical reliability of such INP devices, which is essential for them to be deployed in industrial realities.

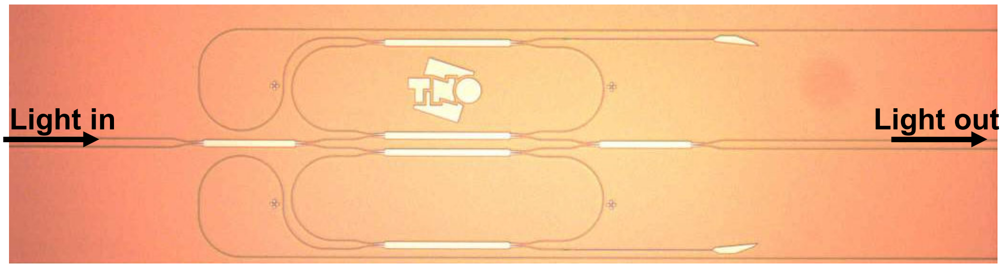

Fig. 1, TNO INP devices including waveguide, multimode interference, and ring resonator are presented. Light is guided into the device, travels through the ring resonators (race track), then is guided out, causing a unique spectrum – the sensing signal. We investigate the reliability of the nanodevices in harsh environments.

Currently, photonic chips are developed and characterized inside the laboratory in a clean-room environment. We need to take these chips out of the clean-room to show how they perform in real-world, for most times, in harsh environments. The aim is to validate the robustness of nanophotonic chips under a number of different extreme conditions. Only with a certificate of reliability in these conditions, can TNO-INP devices fulfil the stringent requirements to operate in harsh industrial applications, allowing further developments into complete commercial systems.

Experiments and Results

The following harsh conditions have been imposed to the INP devices respectively:

1. Pyroshock impact at room temperature (for maritime, aerospace use)
2. Pyroshock impact at cryogenic condition (for space, aerospace use)
3. Long term exposure to cryogenic temperature (for space, nuclear use)
4. Random vibration (for automotive, aerospace, maritime, medical use)
5. Under-water-explosion (for maritime, military use)
6. Climate chamber - high temperature and high humidity (for automotive, medical, space use)
7. Radiation (for medical, space, nuclear use)

These tests were consistent with the extreme levels required by the industries, i.e., space, automotive, maritime, medical or aerospace sector. Correspondingly, parameters of the tests are based on the real operational environments, e.g., NASA or NATO standards. In particular, room-temperature pyroshock simulates the mass-load and acceleration of a rocket launch on ground, whereas cryogenic pyroshock simulates a flying or separation situation in space. Climate chamber and vibration standards are based on the machinery operation in aerospace or automotive. Under-water-explosion tests a violent bomb attack underneath a boat or submarine, causing vertical explosive shock to the chip. The long-term cryogenic scenario is created by immersing the chip in a liquid nitrogen bath (-196 ^{o}C) for a number of hours, to simulate the use in a space, medical or nuclear-operating situation. Radiation (high-energy gamma ray, 100 Gray) shows tolerance beyond the highest treatment in hospital. To give an example, Figs. 2 reveals the typical pyroshock shock response spectrum (SRS) and acceleration time history

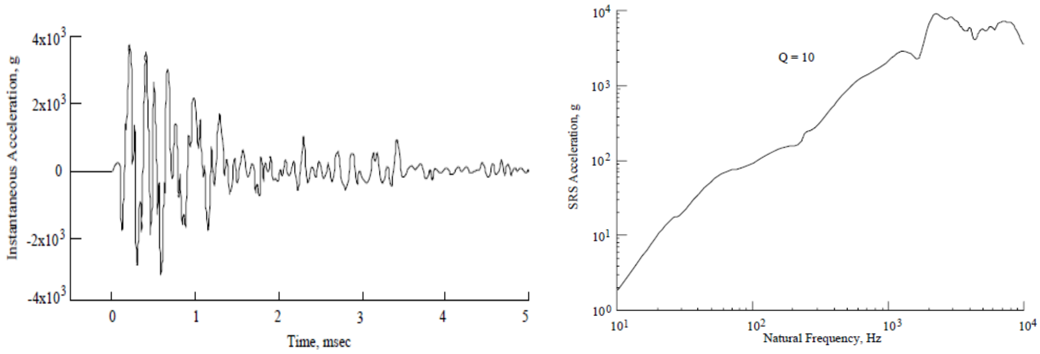

Fig. 2, Typical pyroshock acceleration time history (left) and pyroshock maximal shock response spectrum (SRS) (right).

We call it offline test: 1) The INP devices first are characterized by spectrometer and their spectra are recorded, at room condition; 2) The devices are put into an extreme condition, and experience the condition thoroughly according to the standards; 3) The devices are taken out of the extreme condition and back to the normal room condition; 4) The devices are characterized again by spectrometer and SEM for their spectra and physical structures, at room condition. There were 15 chips exposed to these conditions. Each chip has two dies, each die contains 200 devices including different kinds of waveguides, multimode interference couplers (MMIs), and ring resonators. This makes it 6000 INP devices in total. We pick the most representative ones for spectrum analysis, i.e., approximately 600 devices. For shock and vibration tests, x, y, z directions of the devices are tested, respectively. The result is promising. Spectrum analysis (examples given in Figs. 3) shows that there is no change in light property after the harsh conditions. Only a limited intensity decrease is observed. Presumably, this is due to limited damages to the input / output couplers. Figures 4 summarizes the intensity differences for waveguides and ring resonators. SEM images show that all the INP devices survived all the harsh condition, with no physical damages. Figure 5 shows the typical images. An intensity decrease is observed in all devices, we conclude that indeed the input / output couplers have altered.

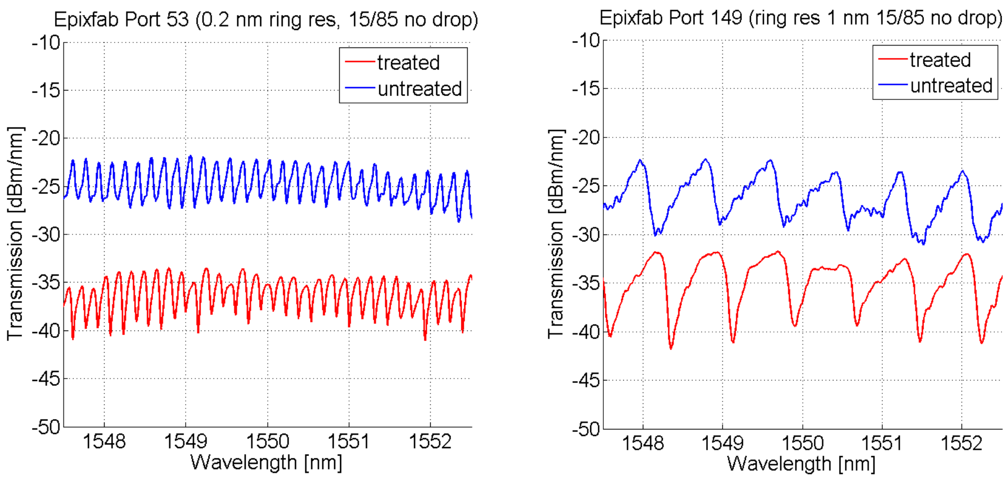

Fig. 3, Spectral comparison of INP ring resonators before and after an extreme condition. On the left, the plot shows the spectra of a 0.2 nm ring resonator (15/85 split, no drop). The blue line indicates the ring's property before a condition (95% humidity and 50 ^{o}C, for 24 hours), while the red line reveals its spectrum after having been experienced the condition. Apart from an intensity drop, there is no obvious property change. The plot on the right gives another example.

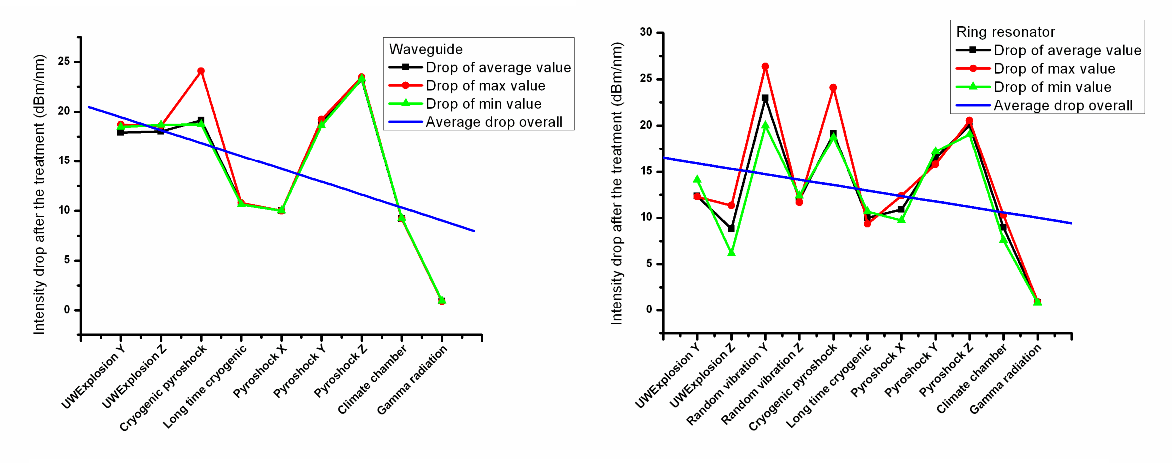

Fig. 4, Left: graph summarizes the intensity drop of waveguides, across the different extreme conditions applied. The plots represent the drops in average value, max value, and min value of the spectra, respectively. Average value of intensity reduction is shown by the blue line. Right: plots summarize the reduction of light intensity of ring resonators for various extreme conditions, in the similar fashion to the left graph.

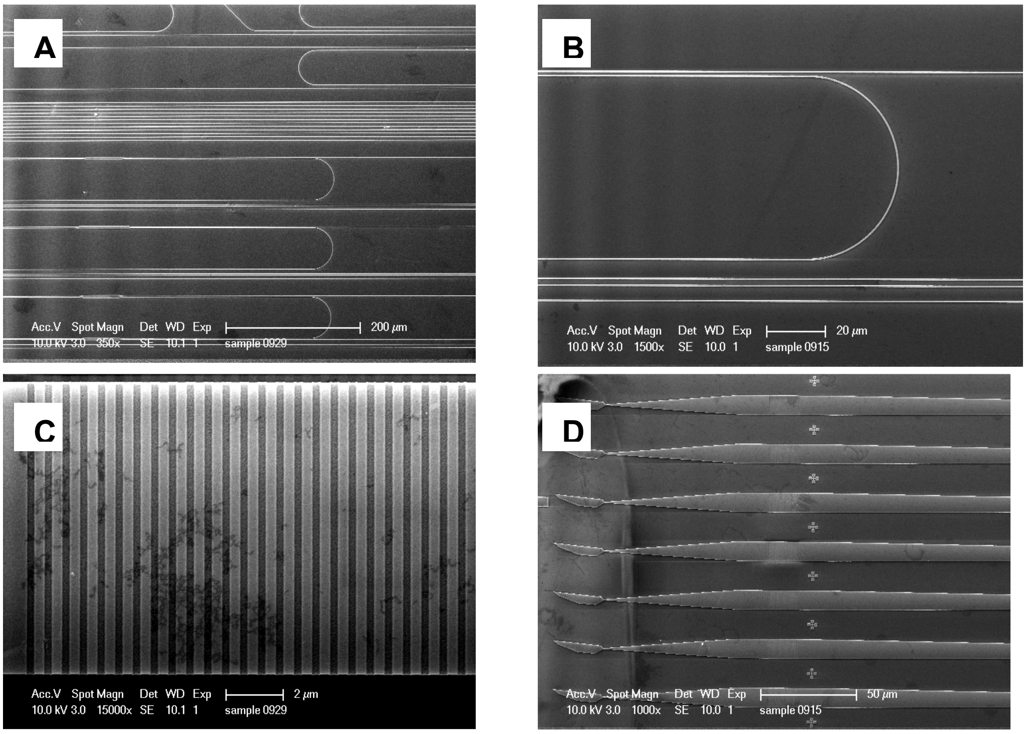

Fig. 5, Typical SEM images of INP devices after the extreme condition. A shows waveguides and ring resonators. B shows a zoom-in on the bend of a ring resonator. Grating couplers, the most vulnerable structure of an INP device, is shown in image C. Image D shows the end parts of the devices. Clearly, there are no physical or mechanical defects caused by the extreme treatments. This result applies to all the harsh conditions employed.

Conclusion

We have performed the offline test, which provided us with the fact that all the INP devices can physically/mechanically survive these harsh conditions, and their photonic nature doesn't vary after the experiences. Yet, does the nature change during its stay in a harsh environment? What does the spectrum look like while the chip is immersed in a cryogenic bath? Can we understand and control its behaviour then? To deploy the INP devices in an industrial reality, these questions must be answered. This is the "online test": 1) Insert the chip in an extreme environment, with components for outside-connections; 2) Connect it to the measurement setup (spectrometer); 3) Monitor the real-time spectrum performance under the extreme condition, simultaneously. With the knowledge gained from the offline tests, we are now entitled to go for the online test. In addition, the survivability study in an operational status is of fundamental interests. Materials science at extreme conditions has been intensively studied, e.g., silicon properties (solid state physics) at low temperature. However, in terms of optical properties at small scale, it is requested to elucidate how the materials behave and how light interaction performs at an extreme condition. We refer to carrier dynamics, random scatterers (Bloch modes), materials properties, and failure analysis. It is a must to understand the physics behind, in order to further guide our engineering work of design, fabrication and test. Thereafter, we are capable to apply the TNO-INP sensors to industrial use in a confident way.