HYBRID PLANAR LIGHTWAVE CIRCUITS FOR DEFENSE AND AEROSPACE APPLICATIONS

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ABSTRACT

We present innovations in Planar Lightwave Circuits (PLCs) that make them ideally suited for use in advanced defense and aerospace applications. We discuss PLCs that contain no micro-optic components, no moving parts, pose no spark or fire hazard, are extremely small and lightweight, and are capable of transporting and processing a range of optical signals with exceptionally high performance. This PLC platform is designed for on-chip integration of active components such as lasers and detectors, along with transimpedance amplifiers and other electronics. These active components are hybridly integrated with our silica-on-silicon PLCs using fully-automated robotics and image recognition technology. This PLC approach has been successfully applied to the design and fabrication of multi-channel transceivers for aerospace applications. The chips contain hybrid DFB lasers and high-efficiency detectors, each capable of running over 10 Gb/s, with mixed digital and analog traffic multiplexed to a single optical fiber. This highly-integrated functionality is combined onto a silicon chip smaller than 4 x 10 mm, weighing < 5 grams. These chip-based transceivers have been measured to withstand harsh g-forces, including sinusoidal vibrations with amplitude of 20 g acceleration, followed by mechanical shock of 500 g acceleration. The components operate over a wide range of temperatures, with no device failures after extreme temperature cycling through a range of > 125 degC, and more than 2,000 hours operating at 95 degC ambient air temperature. We believe that these recent advancements in planar lightwave circuits are poised to revolutionize optical communications and interconnects in the aerospace and defense industries.

INTRODUCTION

Use of fiber optic technology in defense and aerospace industries has been attracting considerable attention recently as a novel platform for in-space communication, remote sensing, guidance navigation and control, lunar descent and landing, and rendezvous and docking[1]. It is mainly driven by the ever increasing demand for high bandwidth and growing pressures towards the use of small-size, light-weight, and low-power components. Meanwhile, recent advances in fiber optic communication technology, especially Planar Lightwave Circuits (PLCs), have opened a number of possibilities for designing on-board optical networks in a cost-effective manner.

Fiber-based optical networks offer a number of significant advantages for defense and aerospace applications over conventional copper-based networks. It has been demonstrated that optical links have the capability to transport mixed digital and analog signals at speed of 2.5 Gb/s per channel[2]. In contrast, copper-based networks which have been extensively employed on aircraft transfer data at rates up to 100 Mb/s. Beyond higher data rates capabilities, optical fibers as a communication channel can transmit light with losses as small as 0.2 dB/km, which can be considered as almost lossless for aerospace applications, allowing the total aircraft power budget to be kept low.

In addition, a number of optical fibers can be bundled in a single fiber optic cable, leading to the significant reduction of the weight of communication hardware. The introduction of the Wavelength division Multiplexing (WDM) technology[3] into optical networks can decrease the number of optical fibers, resulting in further reduction of size and weight and simplicity of cable routing. The photonic integration technology allows the development of ultra compact and light-weight communication components such as optical transceivers. In the reusable launch and space transportation vehicle areas, a battle for each pound of useful payload has justified the unique light-weight advantage of fiber optic communication systems.

The harsh aerospace operating environment imposes many constraints on the engineering and design of avionics systems. The high mechanical vibration and shock are very common for military and aerospace vehicles. A number of contaminants and environmental effects can contaminate open connector surfaces. The communication system should function across a demanding operational temperature range of -55ºC to 125ºC, and should be robust to altitude and humidity changes, sinusoidal and random vibration, and electromagnetic interference. Fiber optic communication technology can meet all these challenges due to its inherent advantages. Moreover, optical fiber presents no spark or fire hazard, and can even be routed alongside or through fuel bays if required.

Optical transceivers are essential components in fiber optic communication systems. They contain both a transmitter and a receiver in a single housing, and can carry upstream and downstream mixed digital and analog signals through a single fiber. To date, aerospace communication systems have relied on optical transceivers which are built based on bulk optic discrete sub-components such as thin film filters (TFF), micro-optic collimating lenses, TO-packaged laser diodes (LDs), and photodetectors (PDs). The high cost of individual components and labor-intensive assembly operations, and the reliability issues associated with the complexity of assembling a large number of critically aligned micro-optic components formed a barrier to further implementation of photonic technologies in defense and aerospace applications.

Planar lightwave circuit (PLC) technology is considered to be the most promising candidate for reliability improvement and cost reduction, and will pave the path to mass deployment of optical networks in aerospace systems. Planar lightwave circuits are devices on which passive elements, active optoelectronic components, and even electronic circuits are integrated on a common silicon substrate. They are fabricated by depositing sequential layers of cladding and core material onto a silicon wafer and subsequently patterning layers using photolithography to form desired functionalities. Several different PLC platforms have been developed for optical communication applications, such as silica-on-silicon, silicon-on-insulator, and lithium niobate. We have successfully developed bi-directional optical transceivers for aerospace applications using the silica-on-silicon platform. In our approach, multiple signals at different wavelengths are multiplexed onto a common fiber using proprietary filtering technology that is monolithically integrated into the PLC chip. This results in fewer discrete components and lower assembly complexity. Active components such as LDs and PDs are passively hybridized with the chip through the use of robotics and pattern recognition techniques with yields in excess of 95%, offering one of the lowest cost platforms for building aerospace-grade transceivers. Because the fabrication of PLC chips and the automated hybridization of active components are done in array form, our hybrid integration approach is ideally suited for the development of multi-channel redundant transceivers.

If one transceiver fails, the others still provide support for critical avionics systems, therefore enabling reliable operation which is particularly desirable in defense and aerospace industries. Moreover, due to our unique planar approach in both optical and electric layers, we have been able to demonstrate remarkable radio frequency (RF) signal integrity in both single and arrayed chips. In this paper, we present the design, fabrication, and performance of the 2.5 Gb/s bi-directional transceiver.

MONOLITHIC INTEGRATION OF PASSIVE COMPONENTS

We adopt silica waveguides as the PLC platform to build various passive components such as couplers, power splitters and combiners, and wavelength filters. The reason for use of silica waveguides is its extremely low propagation loss and the ease of coupling light from laser diodes and from/to optical fibers. In order to reduce the bending radius and to accordingly shrink the chip size, a high refractive index contrast (Δn=1.5%) silica channel waveguide is used in our PLC chips. The single-mode waveguide has a core size of $4.0\ \mu m \times 4.0\ \mu m$ and a bending radius of 2000 um.

Wavelength filters, such as diplexers and triplexers, are important components determining the cost and efficiency of optical transceiver modules. Currently, most commercial wavelength filters are assembled with thin film filters. We have developed a PLC-based wavelength filter which contains a multi-staged Mach-Zehnder interferometer monolithically integrated with a planar reflective grating, as shown in Fig. 1. Mach-Zehnder interferometers have been shown in the literature to have very high transmission efficiency and are capable of splitting wide spectral bands. Planar reflective gratings, on the other hand, possess high dispersion strength that is necessary to split closely positioned channels. Consequently, a combination of Mach-Zehnder interferometers and planar reflective gratings can yield highly performing monolithic chips that require no TFF elements. More details on the PLC-based wavelength filter are given in ref. 4 and 5. Other passive optical functionalities, such as waveguiding, power splitting, and mode-size converting, are also lithographically embedded into the PLC chip, leading to the reduction of the total number of discrete optoelectronic components and of the overall package size.

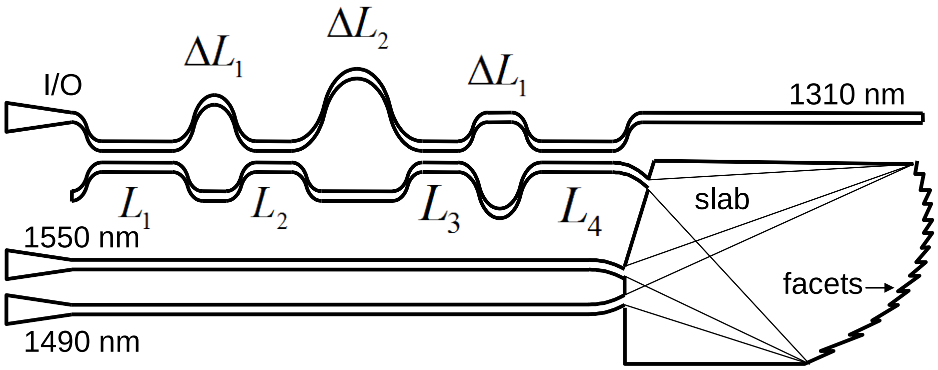
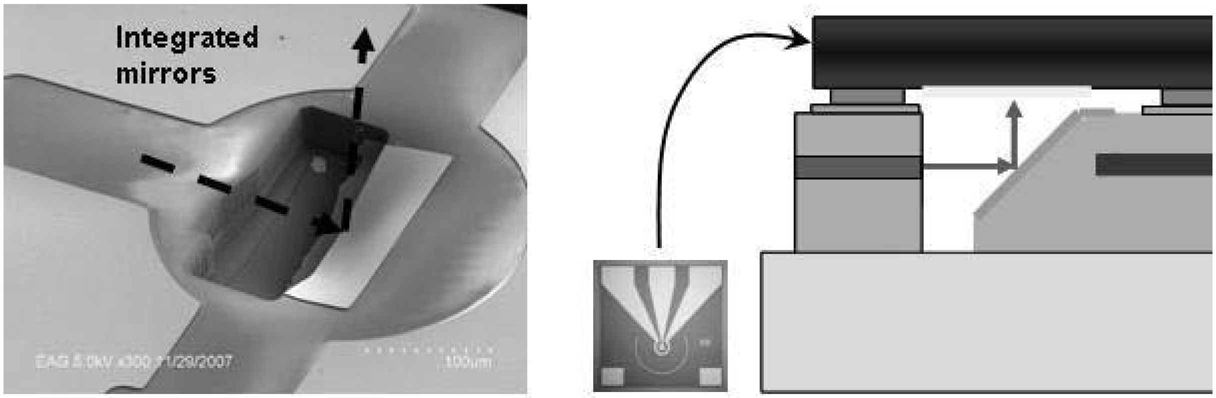


Figure 1. Architecture of the monolithically integrated wavelength filters.

HYBRIDIZATION OF ACTIVE COMPONENTS

Laser diodes (LD) and photodetectors (PDs) are critical components in optical transceivers, which are responsible for the generation and detection of signals, respectively. Our unique hybrid integration approach allows the hybridization of these active components onto the PLC chip in a cost-effective and efficient manner. During the formation of the silica-on-silicon PLC chip, not only the passive optical elements are lithographically defined and embedded in the silica, deep trenches are also formed to accommodate LDs and PDs. To suppress electrical crosstalk, a large number of chickenpox-like deep trenches are formed across the PLC chip, and the LDs and PDs are placed in the opposite corners of the chip.

A spot-size converted laser diode (SSC-LD), which operates at up to 2.5 Gb/s, is used in our chip to simplify the alignment of the laser to waveguides and improve LD-to-waveguide coupling efficiency. A pin-PD with 120 µm light-detecting diameter is employed to form the digital/analog receiver. Both the SSC-LD and pin-PD are flip-chip bonded on the PLC platform. Because the PD is standard surface-illuminated structure, a 45º mirror is needed to couple the light coming out of the waveguide to the PD. With our unique PLC technologies, the 45º mirror can be monolithically integrated on the chip. A V-groove with 45º oriented surface is first formed on the wafer by an anisotropic etching process, then the Ti/Pt/Au film is deposited using advanced chemical vapor deposition technologies, and patterned by liftoff to simultaneously form the integrated reflector, the electrodes, and the PD alignment marks for horizontally passive alignment. The structure of the integrated reflector is shown in Fig. 2. A responsivity of around 0.84 A/W is obtained, meaning that the integrated reflector performs well on coupling the light to the PD.



(a) (b)

Figure 2. (a) SEM image of integrated reflector; (b) Schematic configuration of PD pit structure.

Both LDs and PDs are passively hybridized into deep pits etched into the PLC platform using fully-automated flip-chip bonders. These commercial die bonders operate at very high speeds, with approximately one chip being bonded every 10 seconds. This results in a capacity of well over 10,000 chips per week from a single die bonder. The lateral and vertical alignments between LDs and PDs and PLC platforms have to be precisely controlled to ensure high yield. Lateral alignment is achieved with a pattern recognition system and alignment marks on the PLC platform, as shown in Fig. 3, with corresponding fiducials on the LD/PD chips themselves. The passive hybridization allows for lateral alignment tolerances of nearly +/- 1 um for an excess coupling loss of 0.5 dB.

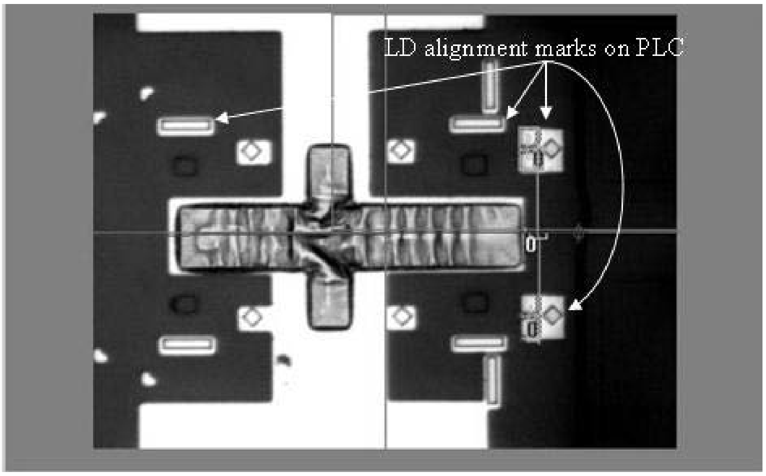


Figure 3. LD alignment marks on PLC for the automated pattern recognition system.

The vertical alignment of the silica waveguide core and the SSC-LD core is very critical to minimize the coupling loss. We fabricate a silica pedestal structure to control the vertical alignment through use of a precision etch-stop layer in the PLC platform[6]. Fig. 4 shows the schematic configuration of a silica pedestal structure. The silica pedestal acts as a precise height reference for the vertical alignment. The solder for the LD is located in a trench system which runs adjacent to the pedestals. The thickness of the molten solder does not change the vertical position of the LD with the help of the pressure applied in the flip-chip-bonding process. Therefore, by carefully controlling etch depths and thicknesses of the silica layer, the vertical alignment accuracy is able to reach +/- 0.2 µm, and the laser-to-waveguide coupling loss up to 1 dB can be obtained.

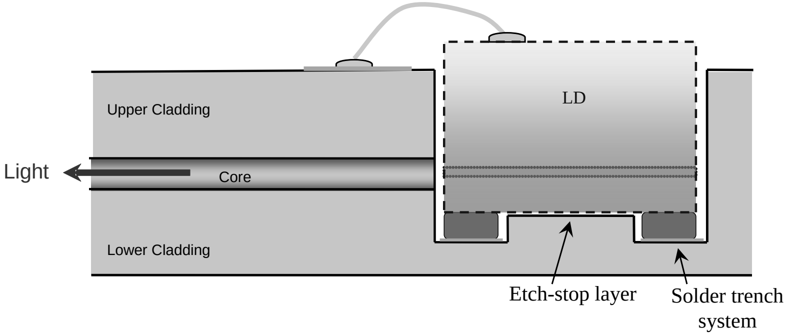


Figure 4. Schematic configuration of a silica pedestal PLC platform.

The hybridized PLC chip is subsequently mounted on a printed circuit board (PCB), together with microelectronic integrated circuits such as the LD driver and transimpedance amplifier (TIA), to form an optical transceiver. All active components are locally encapsulated using semiconductor-grade encapsulants to protect them from humidity and mechanical damage. This allows the packaged transceivers to operate in harsh environmental conditions in a non-hermetic package. Finally, the completed transceiver module is pig-tailed with a single-mode bend-insensitive fiber using an automated pigtailing station. A fully-assembled bi-directional transceiver is shown in Fig. 5. As evident from our

our approach, our PLC hybrid integration technology utilizes a highly automated manufacturing process, allowing high volume production of low-cost transceivers while improving the reliability. Because the fabrication of PLC chips and the automated hybridization of active components are done in array form, our hybrid integration approach is ideally suitable for the development of multi-channel redundant transceivers, which is particularly desirable in defense and aerospace industry.

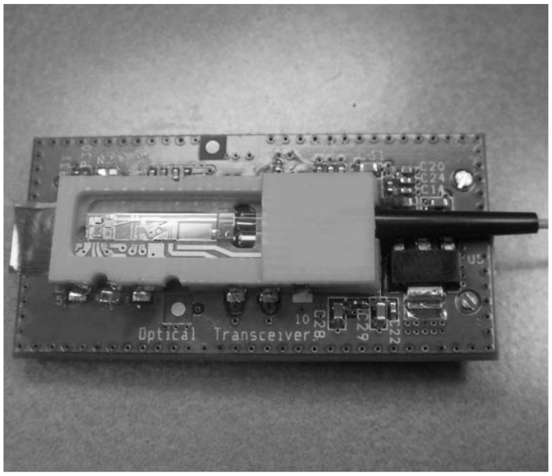


Figure 5. Packaged bi-directional transceiver (lid removed).

PERFORMANCE

Fig. 6 shows the eye-diagram of the 1310nm transmitter channel of the optical transceiver under 2.5Gb/s. The extinction ration is maintained around 10dB. The opening of the eye-diagram can pass the mask test with a good margin. The 1490nm receiver channel shows better than -22dBm sensitivity at 10^{-12} bit-error-rate, as shown in Fig. 6. The cross-talk penalty is well controlled below 0.2dB. No extra RF absorption material is required to reduce the crosstalk during assembly. Most cross-talk penalty comes from the laser switching driving current. DC test shows the optical isolation between 1310nm channel and 1490nm channel is greater than 40dB.

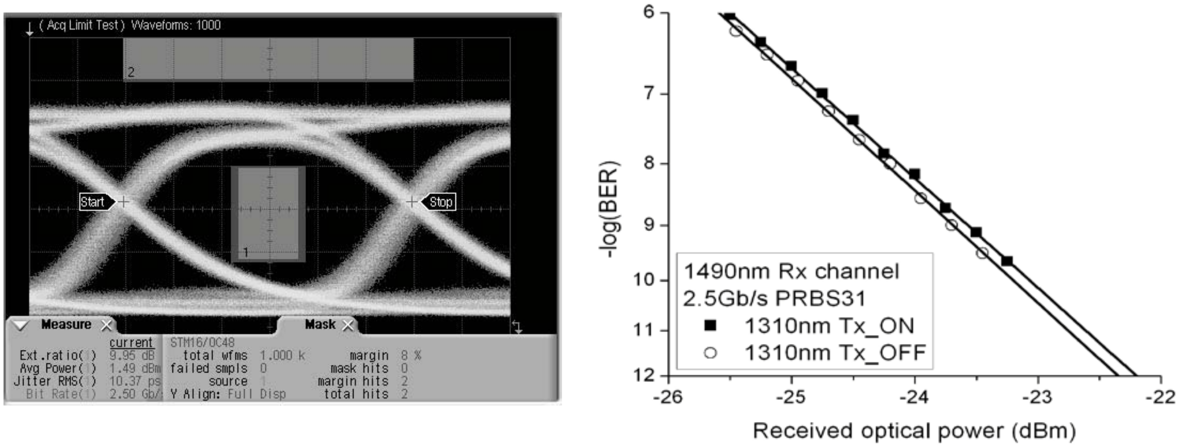


Figure 6. (a) The eye-diagram from the 1310nm transmitter channel of the optical transceiver; (b) The BER sensitivity test for the 1490nm receiver channel. The extinction ration of the 1490nm reference transmitter is 10dB.

The high temperature operation test is also performed to show the reliability performance of our optical transceivers. The optical test results following the full 2001 hours of 95 ˚C operation are shown in Fig. 7. The results demonstrate that our transceivers operate at high temperature of 95 ˚C for more than 2000 hours with no failures.

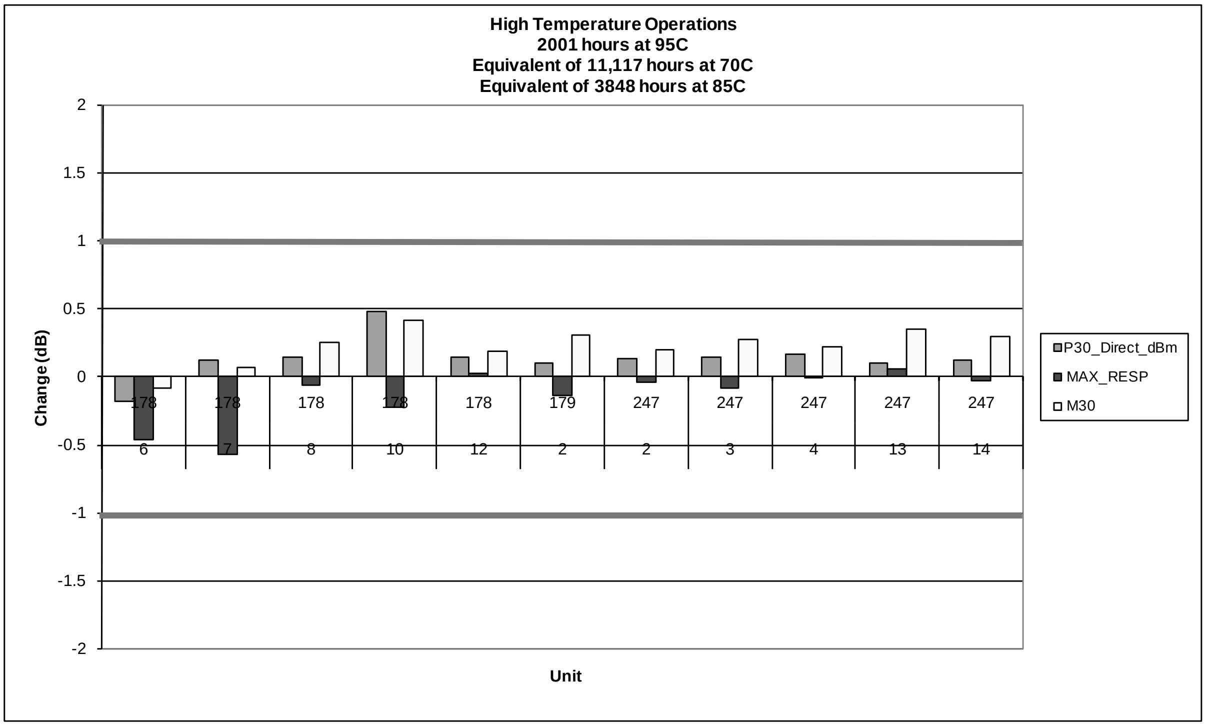


Figure 7. High temperature operation test results of our optical transceivers.

SUMMARY

We described a planar lightwave circuit hybrid integration technology to build fiber optic components and subsystems for defense and aerospace application. Our approach allows for monolithic integration of all passive optical components in a single PLC chip. The hybridization of active components requires no active alignment or manual assembly techniques and therefore is readily suitable for large-scale production. We demonstrate a 2.5 Gb/s bi-directional optical transceiver built using our technologies. The transceiver weighs only 1.9 g and is capable of withstanding high mechanical vibrations and harsh temperature environments.

REFERENCES

[1] R Gardner, I. Andonovic, D. K. Hunter, A. J. McLaughlin, J. S. Aitchison, J. H. March "PHONAV - A photonic WDM architecture for next generation avionics systems", Proc. of IEEE Aerospace Conf. 1999.

[2] S. Bidnyk, M. Pearson, A. Balakrishnan, and S. O'Keefe, "Bi-directional fiber optic transceivers for avionics applications," Avionics, Fiber-Optics and Photonics Conference 2007, Paper ThB 2, Victoria, BC, Canada (October 2-4, 2007).

[3] C. A. Brackett, “Dense wavelength division multiplexing networks: principles and applications”, IEEE J. Select. Areas Commun., 8, 948-964, 1990.

[4] S. Bidnyk, D. Feng, A. Balakrishnan, M. Pearson, M. Gao, H. Liang, W. Qian, C.-C. Kung, J. Fong, J. Yin, and M. Asghari, "Silicon-on-insulator-based planar circuit for passive optical network applications", Photon. Technol. Lett. 18(22), pp. 2392-2394, (2006).

[5] S. Bidnyk, M. Pearson, A. Balakrishnan, M. Gao, D. Feng, H. Liang, W. Qian, C.-C. Kung, J. Fong, P. Zhou, J. Yin, and M. Asghari, "Silicon-on-insulator platform for building fiber-to-the-home transceivers" OFC/NFOEC 2007, Paper PTuM4, Anaheim, CA (March 25-29, 2007).

[6] Young-Tak Han, Sang-Ho Park, Jang-Uk Shin, Duk-Jun Kim, Yoon-Jung Park, Sung-Woong Park, Jongdeog Kim, and Hee-Kyung Sung, “A two-Step etching technique for silica terraces in the PLC hybrid integration.”, IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 16, NO. 11, pp. 2436-2438, NOVEMBER 2004.

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