Design and Analysis of Refractometer Based on Bend Waveguide Structure with Air Trench for Optical Sensor Applications

Jin Hwa Ryu, Woo-Jin Lee, Bong Kuk Lee, Lee-Mi Do, Kang Bok Lee,
Namkyoung Um, and Kyu-Ha Baek

This study proposes a novel optical sensor structure based on a refractometer combining a bend waveguide with an air trench. The optical sensor is a 1 × 2 splitter structure with a reference channel and a sensing channel. The reference channel has a straight waveguide. The sensing channel consists of a U-bend waveguide connecting four C-bends, and a trench structure to partially expose the core layer. The U-bend waveguide consists of one C-bend with the maximum optical loss and three C-bends with minimum losses. A trench provides a quantitative measurement environment and is aligned with the sidewall of the C-bend having the maximum loss. The intensity of the output power depends on the change in the refractive index of the measured material. The insertion loss of the proposed optical sensor changes from 3.7 dB to 59.1 dB when the refractive index changes from 1.3852 to 1.4452.

Keywords: Integrated refractometer, air trench, bend waveguide, optical sensor, planar lightwave circuit.

I. Introduction

A refractive index is a unique optical characteristic of matter, and its precise measurement is a critical factor in various areas, such as chemistry, biotechnology, and environmental monitoring. Active refractometer studies based on various optical devices, such as a ring resonator, slot waveguide, Mach–Zehnder interferometer, directional coupler, waveguides with partially stripped cladding, and bend waveguides, have been conducted [1]–[6]. Studies on optical devices are based on optical fiber devices and planar lightwave circuits (PLCs) [7]. Although there are many studies on optical fiber–based devices (because of their low cost and simple process), they have certain limitations in terms of dimensional accuracy. PLC devices have been studied as an alternative for high-performance optical printed circuit boards. The optical characteristics of an optical device are easily affected by such factors as the structure and refractive index contrast. The curvature of an optical device is particularly sensitive to optical characteristics. PLCs have been actively studied because they can control such variables quantitatively [8]–[9].

To develop a high-performance optical refractometer, increasing the sensitivity of the sensor and improving the reliability through a quantitative measuring environment are essential. A decreased curvature of the optical waveguide causes an increase of the evanescent field. Such a characteristic generates a higher penetration depth, causing the optical device to react more sensitively to the refractive index of the external environment [10]. Note, however, that there is a certain

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Manuscript received Apr. 2. 2014; revised July 16, 2014; accepted July 31, 2014.

This work was partly supported by the ICT R&D program of MSIP/IITP (10041947, development of technologies for high reliable sensor nodes and sensing elements on marine environment) and project (10047806) funded by the Ministry of Trade, Industry and Energy (MOTIE, Rep. of Korea).

Jin Hwa Ryu (gas96@etri.re.kr), Bong Kuk Lee (bklee32@etri.re.kr), Lee-Mi Do (domi@etri.re.kr), Kang Bok Lee (kblee@etri.re.kr), Namkyoung Um (nkum@etri.re.kr), and Kyu-Ha Baek (corresponding author, khbaek@etri.re.kr) are with the IT Convergence Technology Research Laboratory, ETRI, Deajeon, Rep. of Korea.

Woo-Jin Lee (lwj@kopti.re.kr) is with the Nano-Photonics Research Center, KOPTI, Gwangju, Jeonnam, Rep. of Korea.

http://dx.doi.org/10.4218/etrij.14.0114.0413

limitation to the improvement of sensitivity because of the radiation loss caused by a reduction of the bending radius. Moreover, volatile liquid has a limitation in securing a quantitative measurement environment. Therefore, integrated sensor technology with high sensitivity and reliability is required.

The aim of this study is to propose and design an integrated sensor structure that assures improved sensing sensitivity and reliability. This paper describes the design of a highly sensitive sensor based on a waveguide bend with minimum optical propagating characteristics. It also describes a sensor structure whose propagating characteristics are dependent on the measured matter in the quantitative measurement environment.

II. Concepts of Integrated Optical Refractometer

For this study, a refractive index sensor using a waveguide bend and a structure that partially exposes one side of the core layer to improve the sensitivity, integration, and reliability was designed. The sensor was designed and optimized using a beam propagation method. It has a 1 × 2 splitter structure whose output ports have reference and sensing channels. The reference channel was designed for a 3.0 dB insertion loss, whereas the sensing channel was intended to have propagating characteristics that are dependent on the variations of the refractive index. The sensing channel consists of four C-bends connected to create bending radii of R_1, R_2, R_3, and R_4. The C-bend with the R_2 bending radius was designed to expose the sidewall of the core layer. The part where the core layer is exposed was designed to create an air trench structure in a stable measurement environment. The R_1, R_3, and R_4 bending radii were designed to have minimum propagation losses, whereas the structure with the R_2 bending radius, that is aligned with the trench structure, was intended to have the maximum propagation loss. The decreasing bending radius of the waveguide causes an increase in the propagation loss as the radiation mode increases. Note, however, that the index contrast of the waveguide causes a change in the critical angle in the core-clad interface; such loss can be controlled using the characteristics of enhanced light confinement according to high index contrast [11]. In the proposed sensor structure, the reference value is set based on a stable propagation in Channel 1, and the refractive index of the contact matter can be measured by checking the optical characteristics propagated by the external environmental medium in contact with the trench in Channel 2. Figure 1(a) shows a schematic diagram of the proposed refractometric sensor, and Fig. 1(b) shows the U-bend structure of the connected C-bends of the sensing channel.

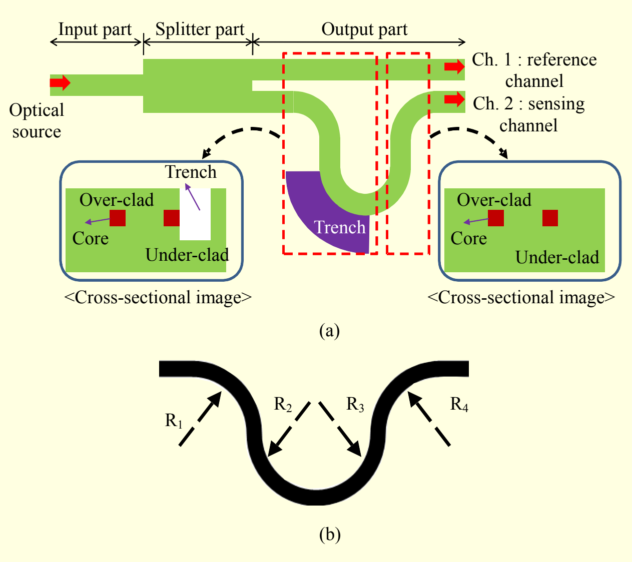

Fig. 1. (a) Schematic configuration of integrated optical refractometer and (b) connected C-bend structures of sensing channel.

III. Design and Analysis of Refractometric Sensor Structure

The optical refractometric sensor was designed as a 6 μm × 6 μm single-mode waveguide, and the difference in the refractive index between the core and the clad was 0.75% (the refractive index of the clad 1.4452) at a 1,550 nm wavelength. The sensor consists of an input port with a straight channel, a splitting part, and output ports with two straight channels. The sensor was designed based on the bending radius of the sensing channel; optical characteristics according to changes in the trench refractive index; dimensional accuracy between the sensor channel and trench; and a 1 × 2 splitter structure. The bending radius of the sensor channel was changed from 0 μm to 25,000 μm at an interval of 100 μm, as shown in Fig. 2.

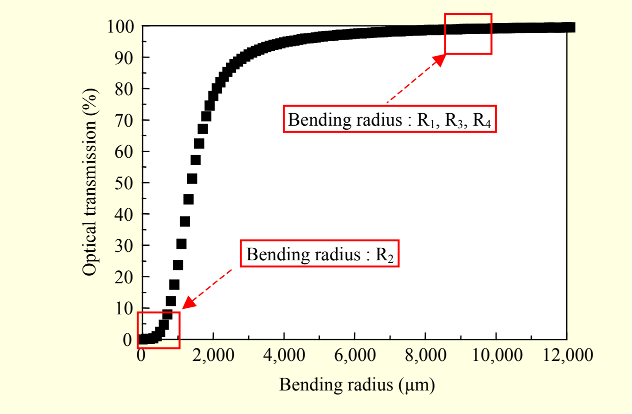

Fig. 2. Optical propagating characteristic according to bending radius.

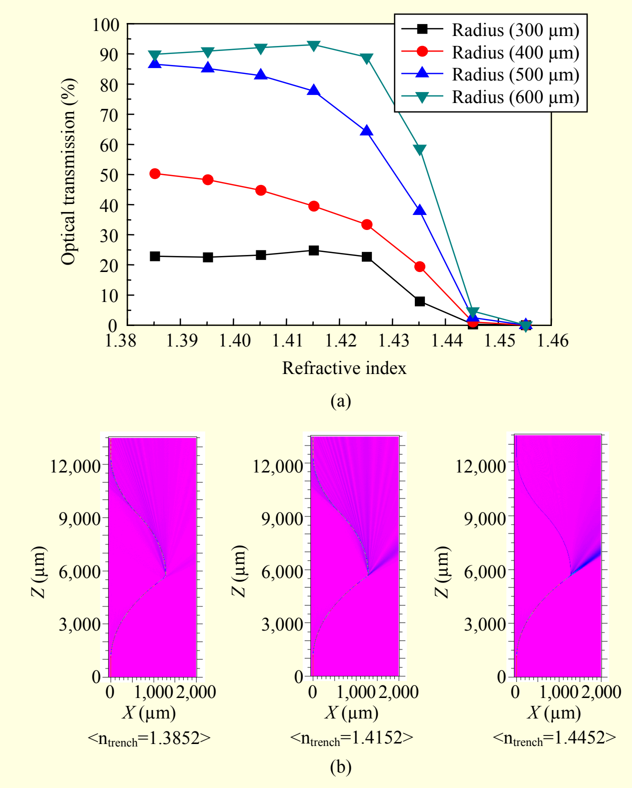

Fig. 3. (a) Optical propagating characteristics of bend structure according to variations of the refractive index of the trench and (b) optical propagating characteristics according to the refractive index of the trench (R_2 of 500 μm).

The increase in the propagation characteristics according to a bending radius increment of 100 μm was confirmed, with 1% propagation at 400 μm, 10% at 800 μm, and 90% at 2,900 μm. Based on the results in Fig. 2, radii R_1, R_3, and R_4 were set to 9,100 μm, which showed 99% propagation characteristics, and the R_2 bending radius was optimized. It was done in an S-bend structure connecting two C-bends involving 9,100 μm and an R_2 bending radius. The refractive index sensitivity, according to the change in the bending radius of the waveguide, and the effectiveness of the sensor were simultaneously assessed. The optical propagation characteristics were confirmed by aligning the waveguide, which has radius R_2 and a trench structure. The trench establishes a quantitative environment, and a 1,000 μm width was set as the bending radius of R_2.

Figure 3(a) shows the optical propagating characteristics of the bend waveguide with the trench aligned. Optimization of the R_2 bending radius was performed within the range of 300 μm to 600 μm, involving a 400 μm bending radius with 1% optical propagation characteristics. The refractive indices varied within a difference range of –0.06 to +0.01 at the 1.4452 trench index. The loss was confirmed to have been reduced owing to the improved propagation characteristics as the bending radius increased. Such characteristics are more obvious when applying a high index contrast. Although the propagation characteristics improved with a high index contrast at a bending radius of 600 μm or more, no changes in optical propagation characteristics from a high index contrast were noted at an index difference of –0.03 or higher. Therefore, the R_2 bending radius was set to 500 μm. Figure 3(b) shows the optical propagation characteristics of the waveguide bend according to the refractive index; *Z* and *X* represent the dimensions for the longitudinal direction and the lateral direction of the optical device, respectively.

The optical characteristics were confirmed according to the accuracy of the dimensional alignment between the bending waveguide and trench. The waveguide had an index contrast of 0.75%, and the trench had the same refractive index as the clad. The U-bend structure (which has R_1, R_3, and R_4 bending radii of 9,100 μm and an R_2 radius of 500 μm) and a trench were used for the optical characteristics according to the accuracy of dimensional alignment. The optical characteristics were confirmed to be within the range of –3.0 μm (decrease of width

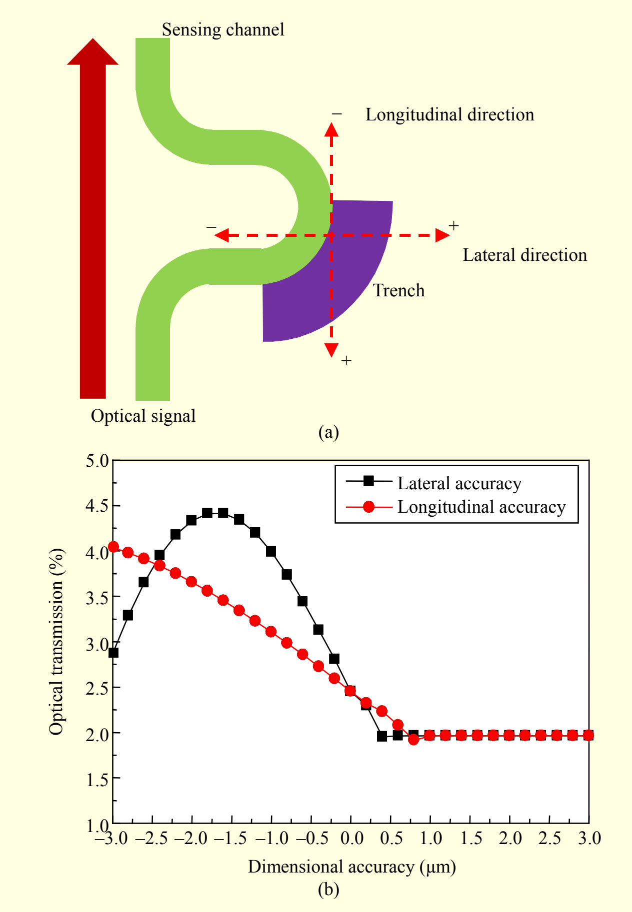

Fig. 4. (a) Schematic configuration of U-bend sensing channel and (b) optical propagating characteristics according to the accuracy of the dimensional alignment.

of R_2 bending waveguide) and +3.0 μm (gap between the waveguide and trench) for lateral and longitudinal accuracies, respectively, as shown in Fig. 4.

Figure 4(a) shows a schematic diagram of the U-bend sensing channel to confirm the alignment accuracy. The characteristics according to the accuracy of alignment of the trench to the waveguide were confirmed, as shown in Fig. 4(b).

The lateral accuracy showed a higher sensitivity than the longitudinal accuracy, with the accuracy of negative-direction alignment, which decreases the channel dimension to the waveguide, being more sensitive than that of the positive-direction alignment; hence the gap. In the longitudinal accuracy, the linear propagation characteristics increased in the negative direction. For the accuracy of lateral alignment, however, the propagation characteristics increased up to 1.6 μm in the negative direction and then decreased at 1.6 μm or higher. This is attributed to a more sensitive width change of the waveguide according to the alignment tolerance in the lateral accuracy. Figure 5 shows the optical characteristics based on the accuracy of lateral alignment according to the refractive index.

Figure 5(a) shows a schematic diagram of the proposed structure improving the alignment tolerance. The interface of the connected C-bend waveguide has of a 30° angle; the R_1-R_2 interface has a 30° angle, and the R_2-R_3 interface has a 0° angle. The waveguide is 6 μm in width in the perpendicular direction. The trench began at the 30° interface, which is the same as the waveguide, and ended at the 0° boundary. The width was designed to be 1,000 μm in the horizontal direction. Therefore, conformal alignment was realized in the R_2-R_3 interface, whereas a dimensional offset was generated by the overlapping structures in the R_1-R_2 interface. In the proposed structure, the dimensional offset was 0.5 μm in the lateral direction and 0.7 μm in the longitudinal direction. The optical characteristics were most sensitive in the R_1-R_2 interface. The proposed structure was also designed to be a cladding taper structure to ensure a stable sensor performance and to control the mode mismatch and Fresnel reflection caused by a change in the local refractive index [11]. The cladding taper was designed to be of the same width as the trench and to be expanded to a 1,000 μm bending radius. Figure 5(b) shows the optical characteristics based on the dimensional accuracy of the structure shown in Fig. 5(a), confirming a 0.5 μm tolerance in the negative direction and a 1.5 μm tolerance in the positive direction. As such, the accuracy of the positive direction was confirmed to have a more stable alignment tolerance than that of the negative direction. The accuracy of the positive direction has a 0.5 μm tolerance and evanescent field characteristics, while the lesser accuracy of the negative direction was caused by the destruction of the waveguide from the decrease in width.

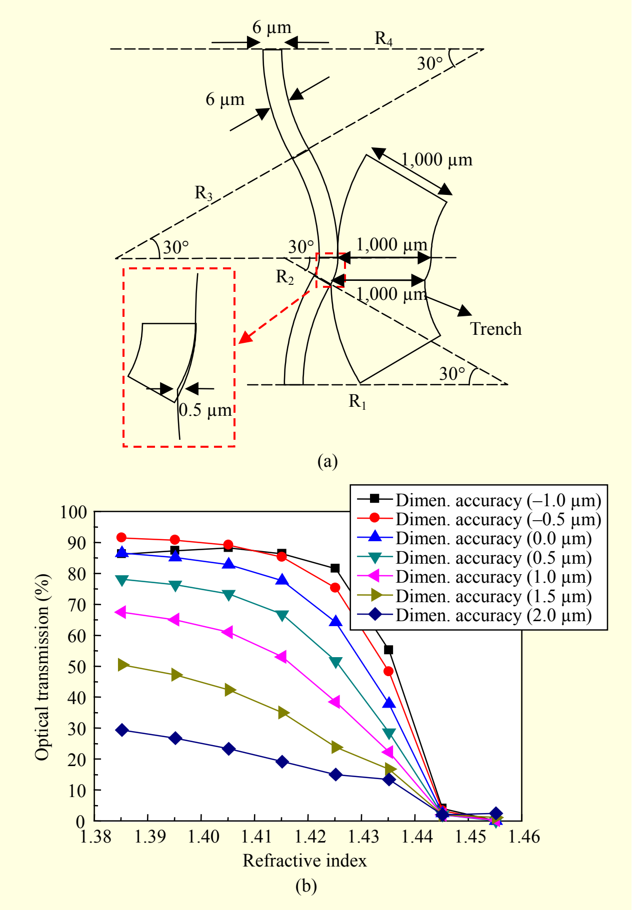

Fig. 5. (a) Detailed structural schematic of the sensing channel and (b) optical transmission depending on dimensional accuracy between the sensing waveguide and trench.

Finally, the sensor characteristics according to the change in refractive index in the proposed structure were confirmed. The sensor has a 1 × 2 splitter structure consisting of reference and sensing channels. The sensor characteristics were observed to be in a refractive index range of 1.3852 to 1.4452 at a 1,550 nm wavelength. To evaluate the effectiveness of the designed sensor, it was designed at a refractive index of 1.0. Figure 6 shows the optical characteristics of the designed sensor.

The rectangular symbol indicates the optical propagation characteristics of the reference channel, confirming a 3.05 dB insertion loss regardless of the refractive index change. The circular symbol shows the optical propagation characteristics according to the change in refractive index in the sensor channel proposed in this study. A change from 42.9% to 0% (exactly 1×10^{-4}%) was shown, corresponding to an insertion loss of 3.7 dB and 59.1 dB, respectively. Since the curvature of the sensing channel was designed for the minimum propagation characteristics based on a clad refractive index of 1.4452, the optical loss increased with low index contrast and decreased with high index contrast. With exposure to air, a 3.5 dB insertion loss was confirmed. This result shows the

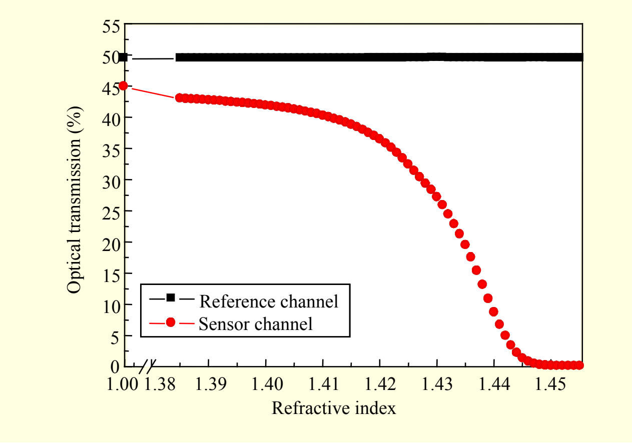

Fig. 6. Optical sensing characteristic according to the refractive index.

extension range of the refractive index measurement and indicates that the sensor proposed in this study can be applied to various areas.

IV. Conclusion

In this paper, a new structure for a refractive index sensor was proposed. The proposed sensor enables high-density optical integration and reliability along with improved process tolerance. To achieve these characteristics, a hybrid 1 × 2 splitter structure integrating a bending waveguide having the minimum propagation characteristics and a trench exposing the core was designed.

The sensing characteristics were confirmed to be within an index range of 1.3852 to 1.4452 at a 1,550 nm wavelength. The reference channel showed a 3.05 dB insertion loss regardless of the change in refractive index, whereas the sensing channel exhibited an insertion loss ranging from 3.7 dB to 59.1 dB depending on the change in refractive index. Based on the refractive index of the clad, the designed sensor showed a high propagation loss with low index contrast and a low propagation loss with high index contrast. It was designed for a structure having a dimensional offset between the waveguide and trench to improve the process tolerance. The proposed sensor in this study can serve as a quantitative measurement environment, having a structure that enables stable measurement of volatile matter.

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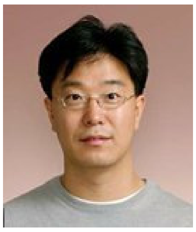
Jin Hwa Ryu received his BS degree in process engineering from Inje University, Gimhae, Rep. of Korea, in 2004 and his MS and PhD degrees in nanofusion engineering from Pusan National University, Busan, Rep. of Korea, in 2006 and 2011, respectively. Since 2011, he has been with ETRI, Daejeon, Rep. of Korea, where he is currently a senior researcher of the IoT Sensor Application Research Section. His research interests are planar lightwave circuit devices, optical interconnection, nano/micro fabrication techniques, polymer optical waveguide devices, and IoT sensors.

Woo-Jin Lee received his BS and MS degrees in electrical engineering from the University of Seoul, Seoul, Rep. of Korea, in 2000 and 2002, respectively. From 2002 to 2006, he was with the Electronics and Telecommunications Research Institute, Daejeon, Rep. of Korea, where he worked on parallel optical interconnection modules for very short reach application and on the development of a laser writing system. Since 2007, he has been with the Korea Photonics Technology Institute, Gwangju, Rep. of Korea. His research interests are optical waveguide devices, optical sensor devices, optical interconnection, and micro-electromechanical systems.

Bong Kuk Lee received his BS and MS degrees in chemical engineering from Dong-A University, Busan, Rep. of Korea, in 1996 and 2001, respectively. He received his PhD in chemical engineering from Osaka University, Japan, in 2005. From 2005 to 2008, he worked as a postdoctoral research fellow for Japan Science and Technology Agency. From 2008 to 2010, he worked as an assistant professor at Osaka University, Osaka, Japan. From 2010 to 2011, he worked as a researcher for Korea Research Institute Bioscience and Biotechnology Daejeon, Rep. of Korea. Since March 2011, he has been at the Electronics and Telecommunications Research Institute, Daejeon, Rep. of Korea, as a senior researcher. His interests include functional materials, nanofabrication techniques, and biosensors.

Lee-Mi Do received her PhD in chemistry from Hannam University, Daejeon, Rep. of Korea, in 1990 and her second PhD in OLED devices from the Department of Biomolecular Engineering at the Tokyo Institute of Technology, Tokyo, Japan, in 1995. She worked at the Electronics Telecommunications Research Institute, Daejeon, Rep. of Korea, from 1996. Currently, her research areas include the development of low-cost OLED lighting processes, nano-electronic devices, nano-imprint devices, and soluble metal oxide TFTT for next-generation flexible electronic devices.



Kang Bok Lee received his BS degree in electronics engineering from Kyungpook National University, Daegu, Rep. of Korea and his MS degree in communication engineering from Chungbuk National University, Cheongju, Rep. of Korea, in 1993 and 2000, respectively. From 1993 to 2000, he worked for LG Semiconductor, Co., Cheongju, Rep. of Korea. Since 2000, he has been at ETRI, Daejeon, Rep. of Korea, where he is currently a section director of the IoT Sensor Application Research Section. His research interests are communication circuits, communication systems, sensor interfaces and system-on-chips.

Namkyoung Um received her BS, MS, and PhD degrees in computer science from Chungbuk National University, Cheongju, Rep. of Korea, in 1999, 2002, and 2007, respectively. From 2007 to 2008, she worked in three roles: as an IT consultant for M&H Business Company, Cheongju, Rep. of Korea, and as an adjunct professor at both Konkook University, Chungju, Rep. of Korea, and Cheongju University of Education, Cheongju, Rep. of Korea. She is currently a senior researcher at ETRI, Daejeon, Rep. of Korea. Her interests include future internet as well as network virtualization and emotion recognition from bio-informatics.

Kyu-Ha Baek received his BS degree in physics from Yonsei University, Seoul, Rep. of Korea, in 1982 and his MS and PhD degrees in electronics from the Department of Electronics Engineering at Chungnam National University, Daejeon, Rep. of Korea, in 1997 and 2012, respectively. He worked at the Electronics Telecommunications Research Institute, Daejeon, Rep. of Korea, from 1983. Currently, his research areas include the development of nano-electronic devices; nano-imprint devices; and MOSFET devices and Metal oxide TFTT for next-generation flexible electronic devices.

http://dx.doi.org/10.4218/etrij.14.0114.0413