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Development of on-chip high performance optical components based on hybrid material system of chalcogenide glass and conventional optical materials

Hansuek Lee
Korea Advanced Institute of Science and Technology

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Hansuek Lee, Juliet Gopinath

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14. ABSTRACT
A completely new approach involving hybrid material structures made of chalcogenide glass on silicon dioxide platform were proposed to avoid serious surface roughness commonly caused by conventional etching process to define optical structures of chalcogenide glass material. Based on this new approach, optical resonators and waveguides were fabricated on a silicon chip, which resulted in 1.5 x 10^5 optical Q factor and 1 dB/m propagation loss. By applying this approach on the previous dispersion control technique based on multiple wedge structures, it was proven that geometry dispersion was be able to be controlled with increased degree of freedom by numerical analysis. As an application of the developed optical components, a supercontinuum generation experiment has been performed. This approach provides a new path to implement high performance optical components, not only with chalcogenide glass as studied in this project but also with potentially other materials having higher refractive index than that of silica glass.

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Name of Principal Investigators (PI and Co-PIs):
- e-mail address : hansuek@kaist.ac.kr
- Institution : Korea Advanced Institute of Science and Technology
- Mailing Address : 291 Daehak-ro E6-6 105, Yuseong-gu, Daejeon 34141, Republic of Korea
- Phone : +82-42-350-1121
- Fax : +82-42-350-1110

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Abstract: Hybrid material structures made of chalcogenide glass on silicon dioxide platform were proposed to avoid serious surface roughness commonly caused by conventional etching process to define optical structures of chalcogenide glass material. Based on this new approach, optical resonators and waveguides were fabricated on a silicon chip, which resulted in 1.5 x 10^5 optical Q factor and 1 dB/m propagation loss. By applying this approach on the previous dispersion control technique based on multiple wedge structures, it was proven that geometry dispersion was be able to be controlled with increased degree of freedom by numerical analysis. As an application of the developed optical components, a supercontinuum generation experiment has been performed.

Introduction: With continuously increasing needs for mid-IR optical systems, chalcogenide glass has been considered one of the most promising material to develop essential components in mid-IR range due to its excellent optical properties such as low material loss and high nonlinearity. The main obstacle, up to now, for the implementation of high performance on-chip chalcogenide components is lack of proper tools (or fabrication techniques) to define micro-structures of smooth side walls which are essential to suppress surface scattering that is the most significant source of optical loss. Therefore, we propose novel approach to develop new type of chalcogenide glass devices to avoid the current fabrication limit. The suggested optical components consist of two different materials, conventional optical materials (such as Si, SiO2, and Si3N4) and chalcogenide glass. The main benefit of this hybrid material system comes from well-developed fabrication techniques of conventional optical materials which guarantee extremely smooth structure surface and unique functionalities of chalcogenide glass such as low optical loss in mid-IR range and high nonlinearity even in near-IR range.

Experiment: We proposed the alternative ways to develop high performance optical components of hybrid structures made of chalcogenide glass and conventional optical materials, SiO_2. By means of well-developed fabrication techniques for the conventional optical materials, the difficult part of chalcogenide glass fabrication can be avoided in hybrid material structures. Figure 1 shows an example, high Q optical resonator with hybrid material structure of SiO_2 and chalcogenide glass. With the suggested approach, chalcogenide glass can be directly deposited on ultra-high-Q resonator surface without etching process to define resonator structure of chalcogenide glass.

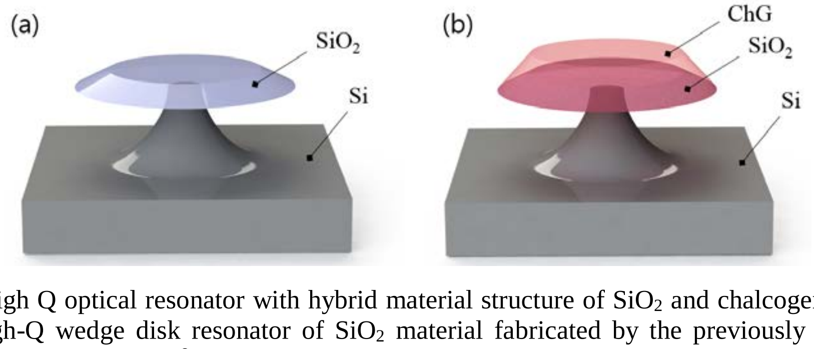

Figure 1. High Q optical resonator with hybrid material structure of SiO_2 and chalcogenide glass. (a) ultra-high-Q wedge disk resonator of SiO_2 material fabricated by the previously developed technique. (Optical Q > 10^8) (b) High Q optical resonator with hybrid material structure by additional deposition of chalcogenide glass on SiO_2 resonator platform shown on (a).

The advantages of this hybrid material system mainly come from relatively easier fabrication process by using conventional optical materials and tunable material properties for the specific applications by adjust optical mode distribution in each materials. In addition, relatively easier integration with the other conventional optical components or devices is expected by means of the interconnection technique for the conventional optical materials.

Figure 2 shows the detailed fabrication process for the suggested high-Q resonators of hybrid material structure. Disk resonator structure was defined on thermally grown SiO_2 material by the optimized photo-lithography and wet-etching process which resulted in extremely smooth etched surface of the device side walls to suppress surface light scattering. After the cleaning and XeF_2 etching process, the ultra-high-Q resonators could be attained. The final additional chalcogenide glass deposition process by thermal evaporation uniformly formed chalcogenide glass film over the whole wafer. The selective deposition on the top of SiO_2 disk platform was naturally achieved by the geometry of SiO_2 disk platform without any etch process for chalcogenide glass.

It was obvious that the optical mode mainly confined in the chalcogenide film due its larger refractive index than that of bottom SiO_2 (2.66 vs 1.45). Figure 3 showed the fundamental mode in the proposed optical resonator of the hybrid material structure (disk diameter: 100 um, wedge angle: 30^o, thermal oxide film thickness: 2um, chalcogenide film thickness: 125 nm) attained from COMSOL numerical simulation. This mode distribution tightly confined in ChG film enabled to exploit the outstanding material properties of chalcogenide glass including low loss in mid-IR range and high nonlinear coefficient. The optical loss performance, namely Q factor of resonators, strongly depends on the surface roughness of the deposited chalcogenide film which is strongly correlated to the original roughness of SiO_2 wedge surface and material deposition condition.

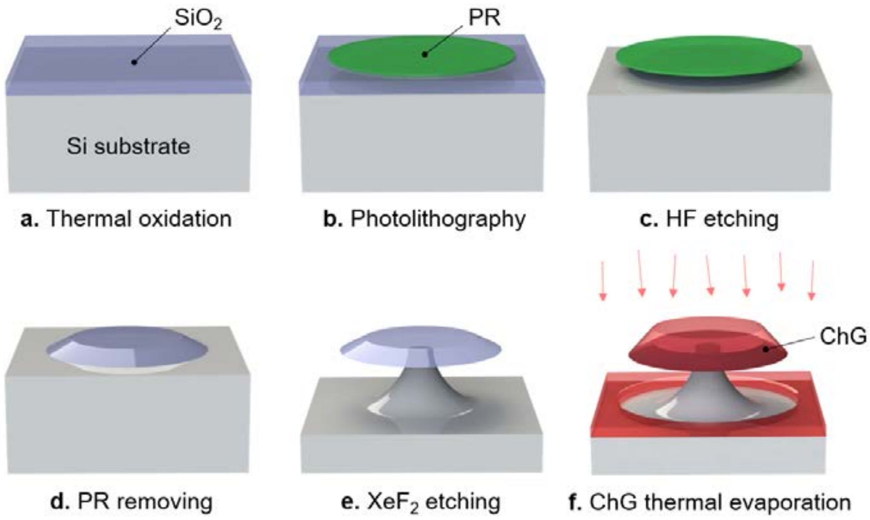

Figure 2. The fabrication process flow for the chalcogenide glass-silica hybrid microdisk resonators.

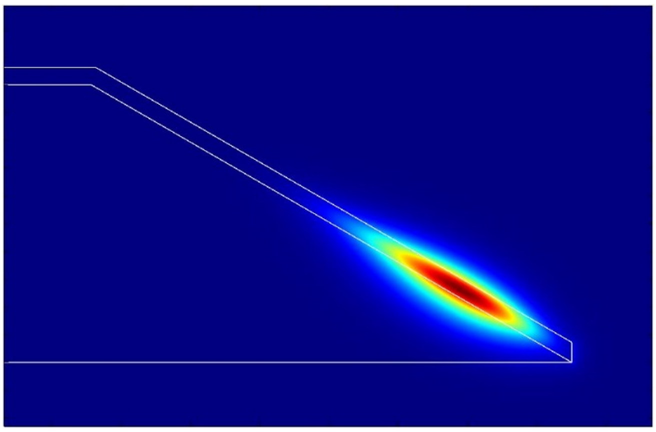

Figure 3. The resonance mode distribution in the high Q disk resonator of hybrid material structure. The optical mode was mainly confined in the chalcogenide glass film with the separation from the edge of disk pattern which had rough and non-uniform material boundary.

Since the smooth etched surface of the bottom SiO_2 resonator which act as a platform for the hybrid material structure was essential, photo-lithography and wet-etch process were optimized. 3 different kinds of photo-resists (PR) were intensively tested under various conditions for PR thickness, exposure dose, soft/hard/post-exposure baking temperature and time, and develop time. Figure 4 shows photo-resist patterns prepared under the condition which PR provider recommended (left) and the optimized condition for smooth etched surface. With this optimized PR patterns, disk resonators were defined on thermal oxide film by wet etch process with buffered oxide etchant. The etch temperature was carefully controlled to minimize etch roughness, and the resulting etched surface was shown on figure 5. Since the roughness was too small to be measured by Scanning Electron Microscope, Atomic Force Microscope was used for the roughness measurement, which resulted in around 0.7 nm RMS roughness. After PR removing and cleaning process, the silicon substrate was undercut by XeF_2 etch process.

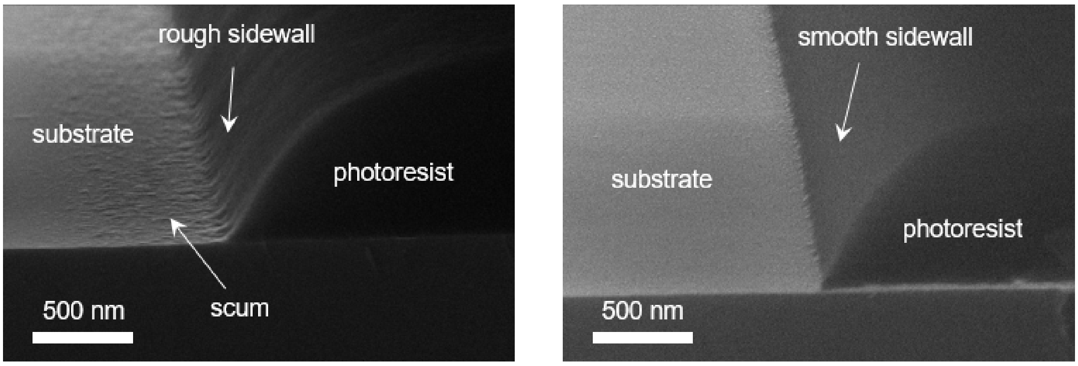

Figure 4. Photo-resist patterns before (left) and after (right) fabrication condition optimization. The pattern on the left side prepared under the condition which PR provider recommended.

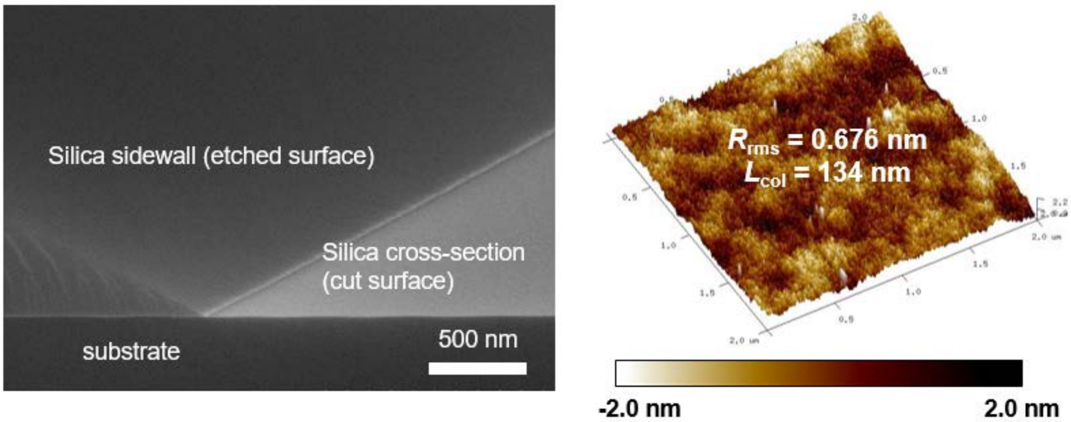

Figure 5. The etched SiO_2 surface roughness measured by SEM (left) and AFM (right). RMS roughness by AFM was around 0.7 nm.

The prepared chips with disk resonators of 13.5 um and 46.5 um diameters were sent to Prof. Won Park group at University of Colorado, Boulder for chalcogenide glass deposition. $Ge_{28}Sb_{12}Se_{60}$ film of 100 nm thickness was deposited on the top of SiO_2 wedge disk platform by thermal evaporation process at a base pressure of $3x10^{-7}$ Torr. Figure 6 shows SEM image of chalcogenide glass / silica hybrid resonator. The uniform deposition of chalcogenide film on the top of silica disk platform was obviously shown on the cross-section image.

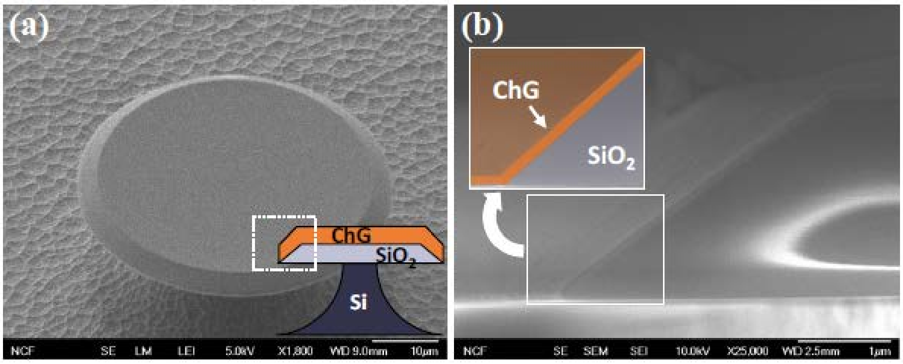

Figure 6. (a) SEM image of chalcogenide glass / silica hybrid resonator. (b) SEM image of cleaved cross-section of the hybrid resonator. (inset: magnified false color SEM image of disk edge cross-section)

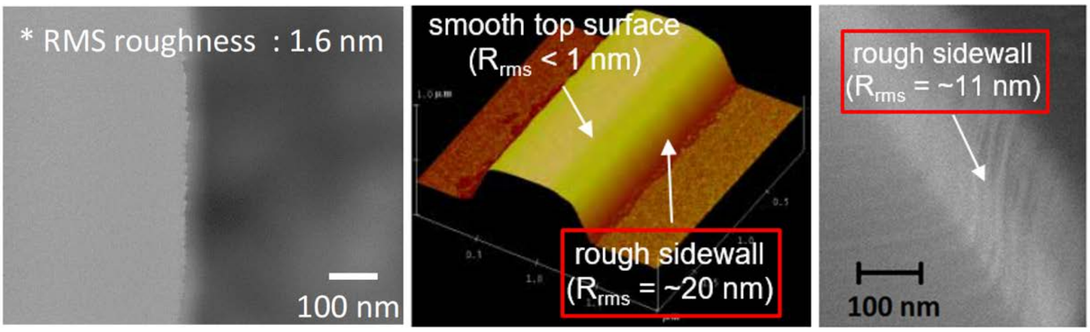

Figure 7. Surface roughness of chalcogenide glass optical components measured by AFM. (Left) optical resonator of hybrid material structure implemented during this project performance. (Middle) chalcogenide glass waveguide defined by liftoff process shown on Optics Express, vol. 15, p. 85531, 2007. (Right) chalcogenide glass waveguide defined by chlorine plasma etching shown on Applied Physics Letters, vol. 106, p. 111110, 2015.

The surface roughness of the deposited chalcogenide glass film was measured by AFM around the edge of the disk pattern where the most serious roughness happens as shown on figure 7 (left). The measured roughness was around 1.6 nm which was much smaller value than the minimum side wall roughness of the chalcogenide waveguides defined by dry etch or lift-off process which had been previously reported by the other groups as shown on figure 7 (middle) and (right). On the SEM image (left), the edge boundary of chalcogenide glass was neither uniform nor sharp due the nature of deposition process. However, as shown on figure 3, the fundamental mode was separated away from the edge, which prevented serious light scattering by this non-uniform edge boundary.

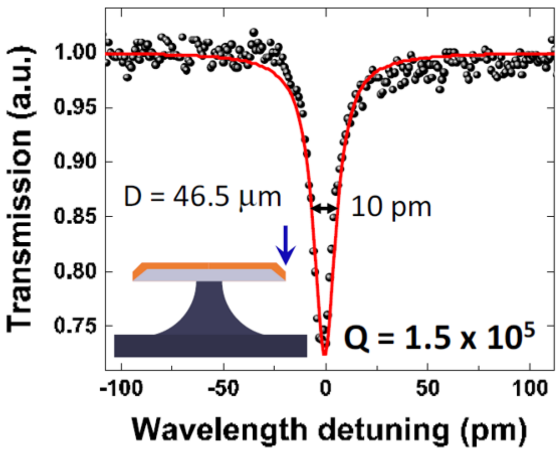

Figure 8. Optical Q measurement by frequency scanning of tunable laser at 1550 nm wavelength. The measured Q was around 1.5 x10^5

Optical Q factor of the implemented hybrid-material resonators was measured by frequency scanning of tunable laser at 1550 nm wavelength range. The measured resonant linewidth was shown on figure 8 which corresponded to 1.5×10^5 Q value, equivalent to around 1.67 dB/cm propagation loss when implemented in the waveguide form. This measured Q factor was comparable to the current record value reported by the other research groups.
Dispersion is one of the major characteristics of high-Q resonators which defines nonlinear efficiency in the cavity. As dispersion control techniques for optical fibers, serval different techniques had been developed to control the dispersion of high-Q resonators such as controlling material dispersion by introducing proper cladding materials and controlling geometric dispersion by modifying waveguide geometry [Nature Photonics, vol. 10, p. 316, 2016]. Immature etch process made on-chip chalcogenide glass devices difficult to employ dispersion control technique especially for geometric dispersion control. During the performance of this research project, we found that geometric dispersion could be precisely controlled without any direct etch process, but by adjusting SiO_2 wedge angle and chalcogenide film thickness. The principle to control the dispersion was shown the figure 9 where dispersion was flattened over wide mid-IR wavelength range by increasing chalcogenide film thickness from 1.1 um to 1.8 um. Since the mode located in the angled chalcogenide glass film, the position of mode, namely effective radius of the resonator, for the certain wavelength was able to be controlled by adjusting chalcogenide film thickness and wedge angle. For example, as shown on the bottom of figure 9, the relative change of effective radius for the fundamental mode at 2um and 7 um wavelength was able to be increased by decreasing the film thickness which resulted in the shift of zero dispersion point to shorter wavelength. In similar way, it was confirmed that zero dispersion point can be shifted to longer wavelength by increasing SiO_2 wedge angle.

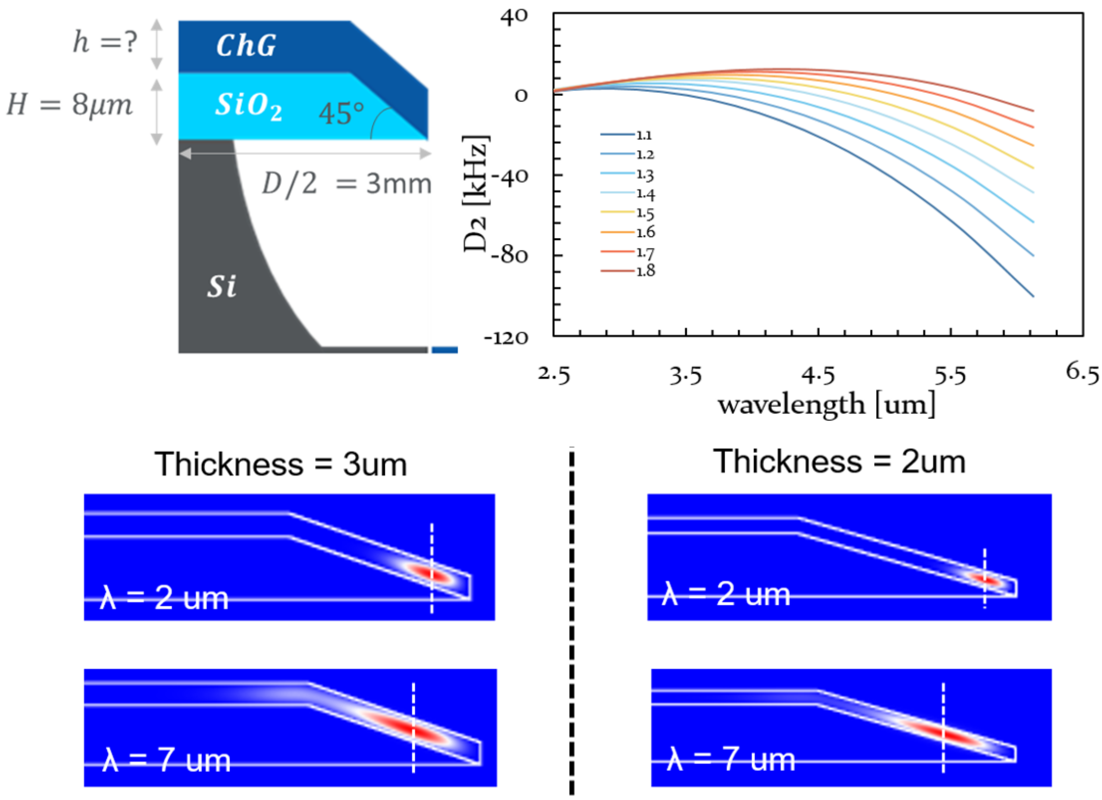

Figure 9. Dispersion control of the ChG – SiO_2 hybrid resonators. (Top) By adjusting wedge disk angle and film thickness, dispersion property wide wavelength range was able to be tuned. (Bottom) The effective radius of optical mode in a cavity changed depending on the wavelength. The longer the mode wavelength, the smaller the effective radius. This trend was able to be modified by controlling wedge angle and chalcogenide film thickness.

This dispersion control mechanism can be implemented in the scheme having more degree of freedom by increasing number of wedge angles. The dispersion characteristics in multiple wedge structure of

SiO_2 resonators were already well analyzed and reported in the previous research [Nature Photonics, vol. 10, p. 316, 2016]. This technique which was previous developed and applied only for SiO_2 wedge resonators can be adopted to control dispersion of any kinds of materials by means of hybrid material system. Figure 10 shows the simplest example of multiple wedge structures which had 2 wedge angles. By adding one more wedge, two additional zero dispersion points were able to be created and shifted between 2 um to 5 um.

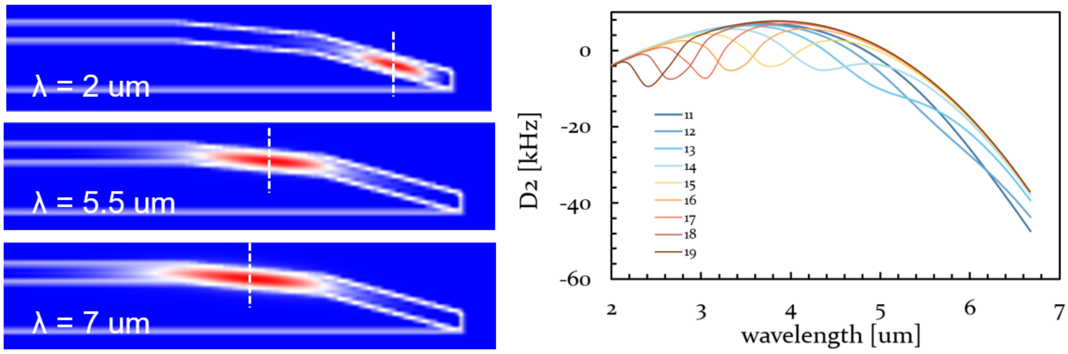

Figure 10. Dispersion control with multiple wedge structure. (Left) The location of fundamental mode at 2, 5.5, 7 um wavelength in multiple wedge structure. The film thickness was 1.5 um. (Right) Dispersion curve of multiple wedge structure with various chalcogenide film thickness from 1.1 to 1.9 um.

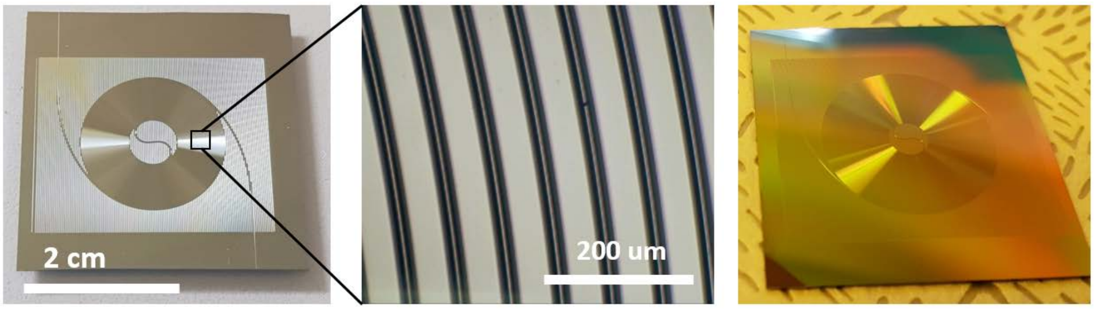

Figure 11. Low loss waveguide of hybrid material structure. (Left) Continuous waveguide having SiO_2 wedge cross-section was fabricated on a silicon chip as a bottom platform structure. (Middle) Microscope image of the waveguide (Right) Chalcogenide glass film was deposited on the top of the platform structure.

This new fabrication approach was also applied to develop low loss on-chip waveguide with chalcogenide material, which is on-chip version of highly nonlinear optical fiber (HNLF) operating in optical telecommunication range. By means of enhanced nonlinearity by chalcogenide glass (around 200 times larger than that of SiO_2), the required length for the certain nonlinear phenomena could be significantly reduced with this hybrid optical waveguide. Basic concept to support the guiding modes in this new type of waveguides was quite similar to that of the ultra-low-loss optical delay lines based on whispering gallery mode structure [Nature Communications, 3, 867, 2012]. The original waveguide guides made of SiO_2 wedge structure acted as a sub-platform on which chalcogenide glass film was uniformly deposited to form the top core layer. Figure 11 shows the fabricated chip which had 5 m length of continuous waveguide. For the waveguide chips, chalcogenide film was deposited by Prof. Duk Choi's group in Australian National University, which had developed on-chip Chalcogenide devices more than 10 years based on conventional direct etch technique. The chalcogenide-deposited chips were shipped back to KAIST where their optical property was characterized precisely.

The optical loss of the developed waveguide was characterized by two different approaches, optical backscatter reflectometry (OBR) method and cut-back method. Unfortunately, the proper loss profile couldn't be attained by OBR method because refractive index difference between the air (n_{air}: ~ 1) and waveguide (n_{WG}: ~ 2.4) was too large, which caused detector saturation due to serious end refraction.

Although several different kinds of index matching oils were applied to reduce this end reflection, the end refraction was always too strong to derive signal propagation profile from the measured data.

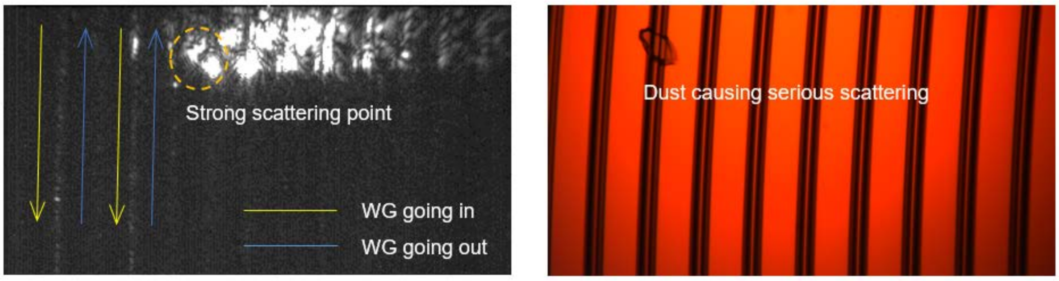

Figure 12. The origin of waveguide disconnection (Left) Waveguide image measured by IR CCD with input signal. A strong scattering point was observed in the middle of the waveguide going in. (Right) Waveguide image with visible CCD. A dust was found in the serious scattering point which killed transmission of the waveguide.

For the cut-back method, the loss of several waveguides in different length was measured in end-fire coupling setup where two lensed fibers were aligned to the input and output port of the waveguide simultaneously. It is well known that, compared to shorter one, propagation loss of the waveguide having longer physical length can be more accurately separated from the measured insertion loss which is combination of propagation and coupling loss. However, there had been always disconnection points in the waveguides of several meter length which prevented proper beam propagation from input to output port. This optical disconnection was caused by a dust which attached on the chip surface at the period after the platform structure fabrication and before the chalcogenide film deposition as shown in figure 12. Since the physical separation caused by international collaboration between KAIST and CU, Boulder (for resonators) / ANU (for waveguide) to deposit chalcogenide glass film was unavoidable to run this research project, it was nearly impossible to solve this contamination issue. Although several numbers of chips were fabricated, we failed to get waveguide chips longer than 1 meter length without such optical disconnection.

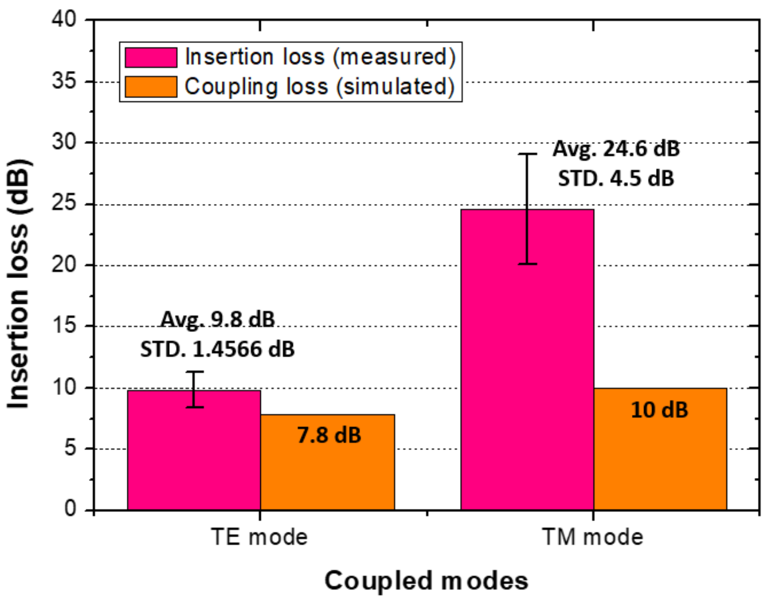

Figure 13. The measured insertion loss of 2 cm length waveguides.
Coupling loss was estimated by numerical analysis.

Therefore, the propagation loss of this hybrid structure was characterized with the waveguide chips of few centimeters in length. The average insertion loss measured for 8 chips having 2 cm length waveguides was shown on figure 13. The coupling loss was estimated by numerical analysis and confirmed with the measurement value. The estimated propagation loss 1 dB/m for TE mode, which

corresponded well with the loss value of 1.67 dB/cm derived from the measured Q factor of 1.5×10^5. The propagation loss of TM mode was estimated to 7.3 dB/m, which was around 4.4 times larger than that of TE mode. This large polarization dependence of propagation loss was originated from the geometry of the waveguides where TM mode had stronger evanescent field. Although the propagation loss of 1 dB/cm was around 100 times larger than the previous record of SiO_2 waveguide, it is acceptable value for the nonlinear process when considering more than 100 times larger nonlinear coefficient of chalcogenide glass compared to that of silica glass.
With the developed hybrid waveguide of 2 cm length, supercontinuum generation experiment was performed. The wavelength and width of input pulse were 1570 nm and 140 fs, respectively. Figure 14 shows output signal spectrum which was measured by optical spectrum analyzer for -13.4, -9.5, -2.1 dBm input pulse power. Although significant spectrum broadening over wide wavelength range, namely supercontinuum, was not observed, we measured an evidence of spectrum broadening as increasing input pump power. Further study will keep continued regardless of the end of this project to achieve efficient supercontinuum generation in mid-IR range by optimizing dispersion of the hybrid waveguide structures.

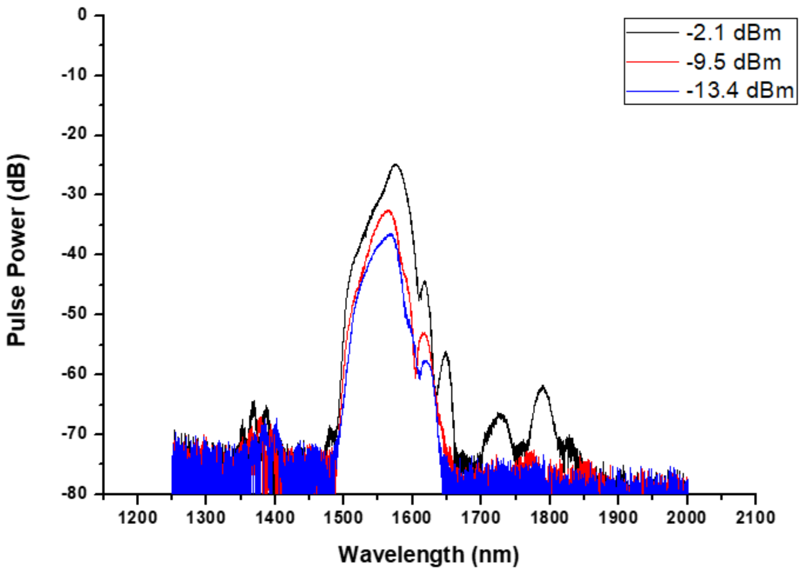

Figure 14. Supercontinuum generation experiment was performed. The output signal spectrum shows evidence of spectrum broadening depending on input pulse power

Results and Discussion: We proposed a completely new approach to define passive optical structures of chalcogenide glass material on a silicon chip without direct etching process which commonly caused serious roughness on the etched surface walls resulting optical loss performance degradation. The idea was proven by implementing optical resonators and waveguides based on this hybrid material structures, which resulted in 1.5×10^5 Q-factor and 1 dB/m propagation loss. We also developed a new technique to control geometric dispersion of on-chip optical components by combining the previous multiple wedge technique and the proposed hybrid material structures. The controllability and degree of freedom of this new dispersion control scheme were investigated and proven by intense numerical analysis. The most important feature of this new approach based on hybrid material system is its compatibility to any other materials currently which don't have proper tool or technique to directly form the materials into a specific geometry. Therefore, this approach paved a way to implement high performance optical components not only with chalcogenide glass as studied here but also potentially with any other materials having higher refractive index than that of silica glass which was used as sub-cladding and platform structure.
Although we successfully demonstrated this new type of hybrid optical components, there are still remained research items requiring further studies to improve the performance of the optical components developed by the proposed technique. Regardless of the end of this research project, we will keep continue to study these three major items. First, coupling efficiency will be enhanced. The geometry of waveguide structure was quite different from conventional on-chip waveguides or optical

fibers. Therefore, there was significant mode shape mismatch between the developed hybrid waveguide and lensed fibers, which resulted in large optical coupling loss for end fire coupling scheme. By modifying waveguide-end geometry, we expect that the coupling loss can be suppressed up to the similar level to that of conventional on-chip waveguides. Second, fabrication uniformity will be increased to fabricate large scale optical structures such as waveguides in few meter length. The dust and particles will be prevented by temporal encapsulation during the shipping. Chalcogenide deposition process will be optimized to increase uniformity and minimize imperfection in the film. Third, one of the most important practical application, namely supercontinuum generation, will be demonstrated, and the experimental result will be compared to the previous results based on conventional on-chip waveguides to verify usefulness of the developed technique.

List of Publications and Significant Collaborations that resulted from your AOARD supported project: In standard format showing authors, title, journal, issue, pages, and date, for each category list the following:

a) papers published in peer-reviewed journals,

- Gumin Kang, Moly R. Krogstad, Michael Grayson, Dae-Gon Kim, Hansuek Lee, Juliet T. Gopinath, and Wounjhang Park, "High quality chalcogenide-silica hybrid wedge resonator," Optics Express, vol. 25, issue 13, pp. 15581-15589, June 2017.

b) papers published in peer-reviewed conference proceedings,

- None

c) papers published in non-peer-reviewed journals and conference proceedings,

- None

d) conference presentations without papers,

- KAIST-CU,Boulder workshop at KAIST, Korea, 14th July, 2017
- KAIST-OIST workshop at OIST, Japan, 20th, Aug, 2018

e) manuscripts submitted but not yet published, and

- None

Manuscripts in preparation

- "Universal method to control geometric dispersion of hybrid wedge resonators"

f) provide a list any interactions with industry or with Air Force Research Laboratory scientists or significant collaborations that resulted from this work.

- For this project, there was strong collaboration with Prof. Gopinath and Prof. Park group at University of Colorado, Boulder who performed AFOSR project. The chalcogenide glass film was prepared and characterized for hybrid resonators by UC, Boulder group.

Attachments: PDF file of the published journal paper was attached.

DD882: As a separate document, please complete and sign the inventions disclosure form.