Regular Papers

Silicon Wire Waveguides and Silicon Microphotonic Devices

Seiichi Itabashi*†, *Hiroshi Fukuda*, *Tai Tsuchizawa*, *Toshifumi Watanabe*, and *Koji Yamada

Abstract

We report on our recent progress in developing microphotonic devices based on Si-wire waveguides, which promise size reductions, high-density integration, and active functions due to their strong light confinement. We have made low-loss Si-wire waveguides and an excellent spot-size converter. Various passive optical components, such as branches and wavelength filters, that exhibit excellent characteristics have also been developed. We have developed and confirmed the feasibilities of active functional devices, such as a low-power-consumption thermo-optic switch, an all-optical path-routing switch, and wavelength conversion devices.

1. Introduction

A future optical network system requires economical multifunctional optical devices with low power consumption. The key to achieving multiple functions is to miniaturize and integrate various kinds of passive and functional optical devices. Reducing the size of optical devices will also lower their power consumption to below that of ordinary-sized devices. Therefore, mass production techniques for small devices are necessary to make optical devices economical. Microphotonic devices based on Si-wire waveguides could satisfy these requirements [1].

Si-wire waveguides exhibit strong light confinement, which allows the core size for single-mode propagation to be less than 1 µm, and a sharp bend with a bending radius of only a few micrometers is possible [2]. These features should enable us to miniaturize optical circuits and integrate them. Furthermore, we can use existing silicon fabrication technology and SOI (silicon-on-insulator) substrates for Si electrical circuits. This will make waveguide pattern formation easy, and it will be advantageous for mass production, resulting in economical optical devices. Silicon microphotonics technology has recently been developed in many organizations. Many kinds of optical circuits are being fabricated and evaluated [3]. Furthermore, electrically controlled MOS (metal oxide semiconductor) high-speed modulators [4], [5], silicon Raman lasers [6], and other such devices are being developed. If the fabrication technology for these devices becomes practical and integrated, it will have a strong impact on telecommunications systems and on many industries. That is why we have been developing Si microphotonics technology.

2. Si-wire waveguides

A Si wire waveguide is fabricated on an SOI wafer, as shown in **Fig. 1**. The structure consists of a silicon core and silica-based cladding that have refractive indices of

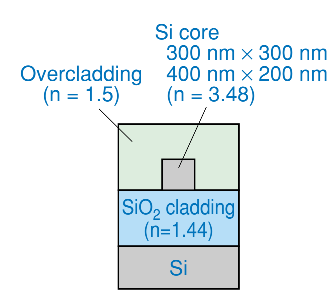


Fig. 1. Structure of Si-wire waveguide.

† NTT Microsystem Integration Laboratories
Atsugi-shi, 243-0198 Japan
E-mail: itabashi@aecl.ntt.co.jp

3.48 and 1.44–1.50, respectively, yielding a refractive index contrast as high as 40%. The core must be about 300-nm-square or 200 nm × 400 nm to provide single-mode propagation at communication wavelengths around 1500 nm. These waveguides are much smaller than silica-based ones whose core sizes are about 7 µm. They confine light strongly in the core and this strong confinement allows sharp bends with radii of only a few micrometers. These features should enable us to make very small optical circuits and integrate them. They should also make it easy to achieve a power density of over 100 MW/cm^2, which is high enough to induce nonlinear effects, such as four-wave mixing (FWM) and carrier creation in silicon by two-photon absorption. Therefore, Si-wire waveguides can be used to make passive functional optical elements, and they also have the potential to be used in active optical components based on carrier or nonlinear effects.

3. Problems in Si-wire waveguide systems

There are two serious problems for systems using Si-wire waveguides. One is the large propagation loss, which greatly reduces the intensity of transmitted light, making it almost impossible to construct optical circuits. In the early stages of this study, the propagation loss was about 60 dB/cm. The other problem is the large coupling loss when Si-wire waveguides are connected to external circuits, which generally use optical fibers. The waveguide core is much smaller than the mode field size of an ordinary optical fiber (about 9 µm in diameter). This large difference produces a coupling loss as high as 20 dB per connection. Moreover, high facet reflection at the connection causes a fatal Fabry-Perot resonance, which degrades the wavelength characteristics.

4. Solutions

4.1 Reduction of propagation loss

The main cause of the propagation loss is scattering at the sidewall of the waveguide's core. Because the light is strongly confined in the small core, the nanometer-scale roughness of the sidewall scatters the light and causes propagation loss. Therefore, we improved the fabrication method to reduce the sidewall roughness.

These waveguides are fabricated by etching Si. The etching process uses resist mask patterns that correspond to the waveguide. The sidewall roughness is mainly introduced by imperfections in the resist pattern. The etching process can also add roughness depending on the etching conditions. Therefore, lithography and etching are the keys to making a smooth sidewall. We used improved EB (electron beam) lithography and ECR (electron cyclotron resonance) plasma etching methods. The waveguide patterns were delineated on the resist with the EB-X3, a variable-shaped EB writer with an acceleration voltage of 100 kV developed as an X-ray mask writer [7]. Although this EB writer has a high throughput, it is generally unsuitable for making smooth patterns, especially curved lines. Therefore, we had to improve the writing method. To form smooth patterns with uniform widths, we optimized the EB shot size to reduce fluctuations and developed a multiple-exposure method in which the EB shot is shifted incrementally. Moreover, we reduced proximity effects in the EB data. These improvements significantly reduced the roughness of the resist patterns. To transfer the smooth resist pattern to the Si faithfully without adding roughness, we used ECR plasma etching with a fluoride gas. ECR plasma etching with the SF_6-CF_4 gas mixture can make Si patterns with vertical sidewalls [8]. This process can be performed at low gas pressures of 0.1 Pa or less. Moreover, the wafer is irradiated with only low-energy ions, which is a big advantage for making smooth sidewalls because little damage is caused and hardly any redeposition of reaction products occurs during etching. For smooth sidewall etching, it is important to select appropriate plasma conditions and an appropriate material for the etching mask. We found that an SiO_2 hard mask gave us good results.

Scanning electron microscope (SEM) images of Si wires and the tip of the Si taper obtained after the fabrication process improvements had been made are shown in **Fig. 2**. The straight and curved patterns

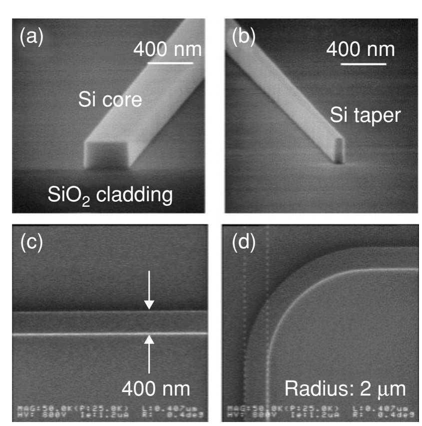


Fig. 2. SEM images Si-wire waveguide.

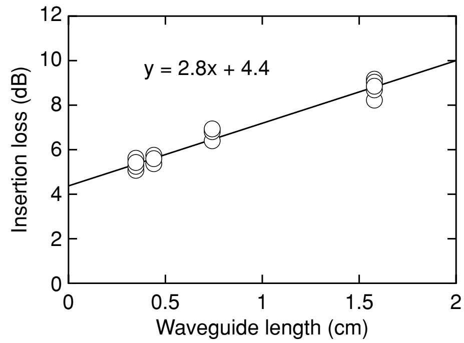


Fig. 3. Propagation loss.

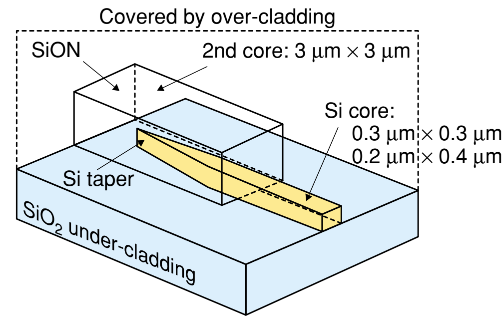


Fig. 4. Structure of spot size converter.

were both very smooth, as can be seen in the figure. We also achieved smooth vertical sidewalls with a width error of less than 10 nm from the designed value.

Some recent propagation loss values measured for waveguides with a core size of 400 nm × 200 nm are shown in **Fig. 3**. We measured the insertion loss for the TE (transverse electric) mode using waveguides of different lengths at the wavelength of 1550 nm. We obtained a loss of 2.8 dB/cm. The rms roughness was estimated to be less than 2 nm [9]. Although this loss is very large compared with that of a silica waveguide, Si-wire waveguides can be used to make ultrasmall circuits in an area less than 1 cm square, so the loss is small enough to make practical devices.

4.2 Reduction of coupling loss

To solve the problem of large coupling loss caused by the large mode field size difference, we developed a spot-size converter [10]. Its structure is shown in **Fig. 4**. The converter has a Si adiabatic taper that gradually becomes narrower toward the end and a second low-index waveguide that covers the taper [2]. Typically, the Si taper should be longer than 200 µm, and the tip of the taper should be less than 100 nm wide. The second waveguide has a core about 3 µm square and an index contrast of about 3% relative to the overcladding. To improve the durability and reduce the loss, we used inorganic materials for low-index waveguides because they have advantages in terms of optical absorption and humidity resistance. For the inorganic spot-size converter, we chose SiON and SiO_2 films as the second core and cladding materials, respectively. These films were grown by plasma-enhanced chemical vapor deposition. The refractive index of the SiON film was controlled over a wide range by adjusting the flow rate ratio of O_2 and N_2 while maintaining a fixed flow rate of SiH4. The deposition rate was about 100 nm/min.

This spot-size converter enabled us to conduct experiments under severe conditions in which high power light was input to the waveguide. The converter did not deteriorate even when the input power was 23 dBm.

The coupling loss per connection can be estimated by subtracting the propagation loss of the Si-wire waveguide from the total insertion loss. The coupling loss per connection was derived as 0.5 dB for the converter made of SiON when optical fibers with a mode field diameter of 4.3 µm were connected to the waveguide ends [2], [11]. We also evaluated the coupling loss for a conventional fiber with a mode-field diameter of 9 µm and found it to be about 2.5 dB per connection. The transmission spectrum was flat between 1450 and 1700 nm. Moreover, no significant ripples were found in either transmission spectrum, indicating the absence of fatal reflections in this experimental system.

5. Passive optical components

After solving the serious problems with propagation and fiber coupling losses, we fabricated and evaluated passive optical components having a very small size and basic optical functions [2].

5.1 Branches

Optical waveguide branches are indispensable for constructing various optical devices. We developed two types of branch: a multi-mode interference (MMI) branch and a directional coupler. An SEM image of a fabricated MMI branch is shown in **Fig. 5(a)**. The branch consists of a simple rectangle with three waveguide ports. The device has no high-angle structures, so accurate fabrication is possible. Moreover, the sensitivity to geometrical errors is essentially low in MMIs. The transmission spectra are shown in **Fig. 5(b)**. They were calibrated using a neighbor-

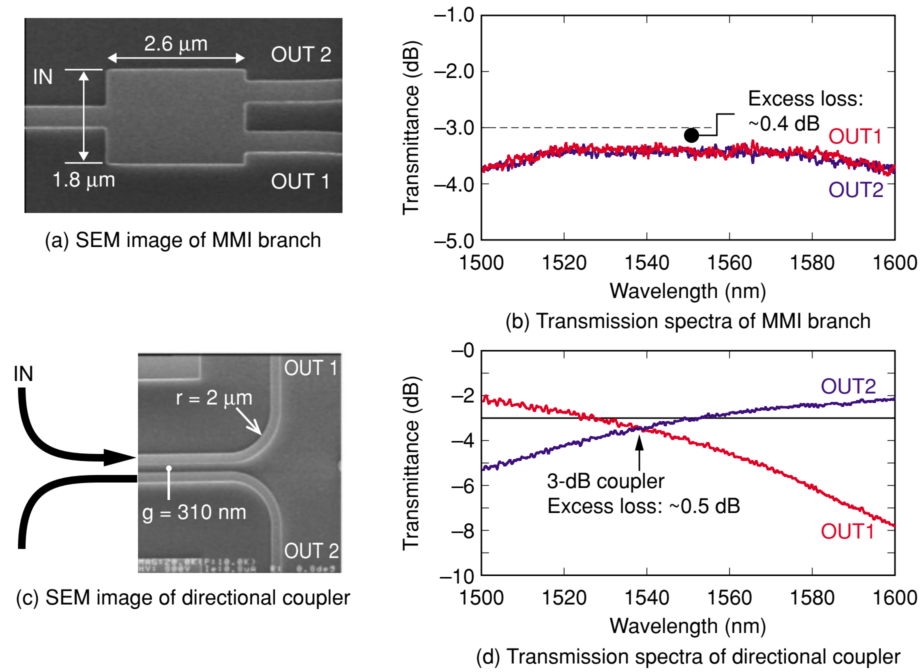


Fig. 5. MMI branch and directional coupler.

ing simple Si-wire. The spectra of the two output ports agreed very well and were very flat within a wavelength range of 100 nm. Moreover, the measured excess losses were as low as about 0.4 dB.

An SEM image of a fabricated directional coupler is shown in **Fig. 5(c)**. The coupler is 13.75 µm long and the coupler gap is 310 nm. The bending radii are ultrasmall (2 µm) to reduce excess coupling. The coupler's transmission spectra, shown in **Fig. 5(d)**, are typical of those for directional couplers. At the wavelength of 1538 nm, the coupler worked as a 3-dB coupler. As a result of the ultrasmall bending radii, the excess loss was about 0.5 dB.

5.2 Filters

5.2.1 Ring resonator

The add/drop filtering device is one of the most attractive passive optical components. As a narrow-band add/drop device, we have developed high-Q ring resonators. The measured drop port spectrum is shown in **Fig. 6**. The resonance bandwidth was very narrow (80 pm) and the quality factor Q was as large as 20,000. In spite of its very high-Q value, the ring had a practical transmittance of -3 dB. A device with such a high Q value and high transmission might be used as a channel drop filter for dense WDM systems.

5.2.2 Lattice filters

Since the free spectral range (FSR) of the ring res-

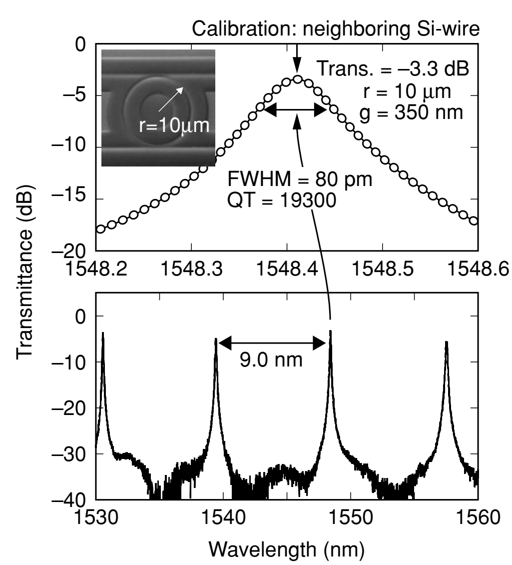
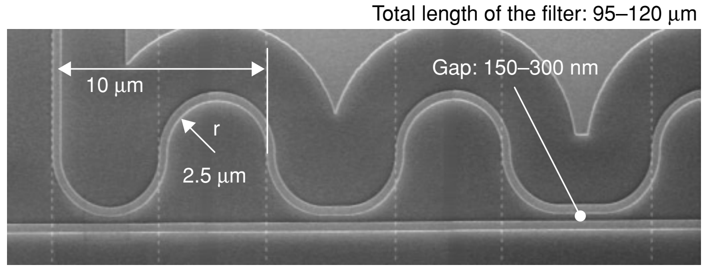
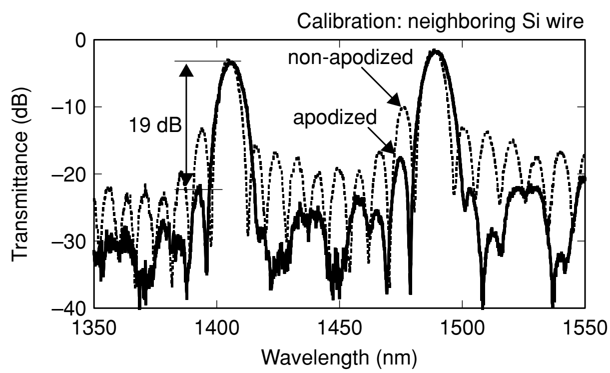


Fig. 6. Drop port spectrum of ring resonator filter.

onator is small, around 10 nm, as shown in Fig. 6, we developed lattice filters [12], [13] as add/drop filters with a large FSR. However, their channel crosstalk was around -10 dB, so we had to greatly reduce this. To reduce the crosstalk, we developed an apodized lattice structure. Part of the apodized lattice structure is shown in **Fig. 7(a)**. A snake-like delay line was made with an arc having a radius of 2.5 µm that periodically encounters a straight section containing the



(a) SEM image



(b) Drop port spectra

Fig. 7. Apodized lattice filter.

directional couplers. The lengths of the couplers were modified for apodization*. The measured transmission spectra of the drop ports for apodized and non-apodized filters are shown in **Fig. 7(b)**. These filters exhibited beautiful channel dropping characteristics. The extinction ratio of the main to side-lobe peaks, which determines the crosstalk, was greatly reduced by the apodization, so this is a very important technique for achieving low-crosstalk filters for practical WDM systems.

6. Switching and active optical devices

Here, we describe some active optical devices in which output light is controlled by an external input such as electrical or optical signals. These devices exploit the advantages of Si, which enabled us to achieve multiple functions and low power consumption.

6.1 Micro thermo-optic switch

The first example is a thermo-optic (TO) switch controlled by external heating. The TO effect is about ten times larger for Si than for silica, so a Si-based TO switch can be expected to significantly reduce the electrical power needed for switching operations compared with the conventional silica-based ones. The structure of our fabricated Si-based TO switches is shown in **Fig. 8**. The design is a Mach-Zehnder interferometer consisting of two 1 × 2 MMI branches or directional couplers and two waveguide arms equipped with thin-film heaters. The transmission characteristics of the TO switch for TE mode operation when electrical power was applied to the heater of one arm are shown in **Fig. 9(a)**. The power required to change the transmittance from maximum to minimum was 70 mW. At that power, the extinction ratio was 34 dB. We estimated the power consumed by the waveguide heaters to be 30 mW. The power consumed by the wiring was 40 mW. This TO switch has the potential to provide switching operations with low power consumption below 10 mW if the additional structures such as heat insulating grooves are added. The optical switching response when a square-wave pulsed voltage of 3.5 V with a 600-µs width was applied is shown in **Fig. 9(b)**. The rise and fall times were both less than 200 µs. Fast switching was achieved mainly because the cladding of the Si-wire waveguide was thin, so the heat flowed rapidly to the Si substrate. We also fabricated 2 × 2 TO switches by using two 3-dB directional couplers,

* Apodization: the method of changing the coupling strength of the directional couplers

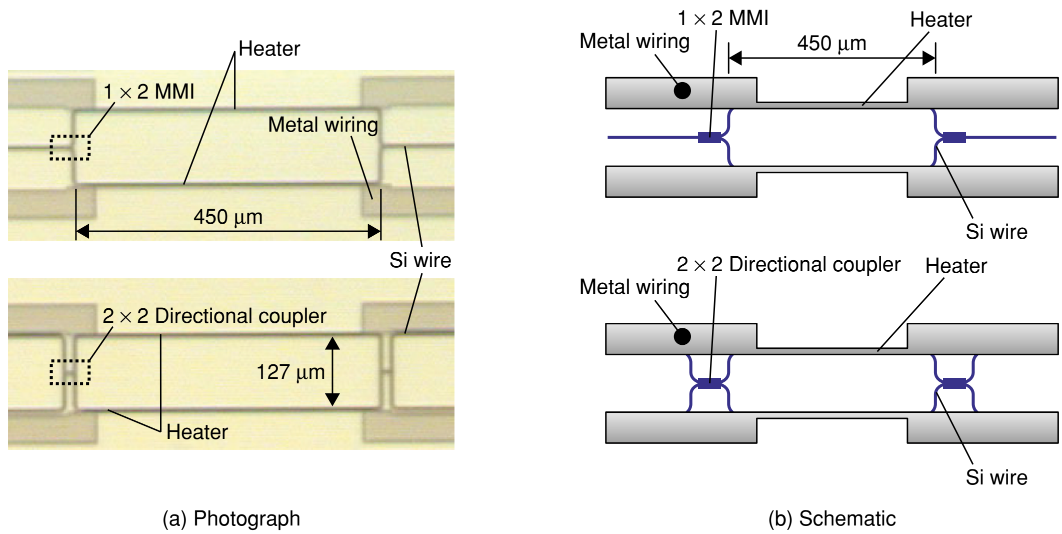


Fig. 8. Optical microscope image of MZI TO switch.

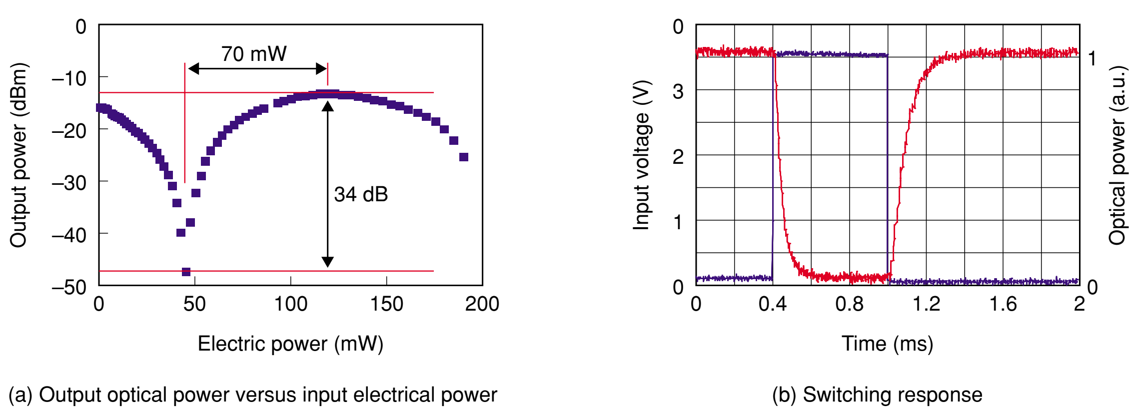


Fig. 9. Characteristics of TO switch.

as shown in Fig. 8, and we obtained similar switching characteristics to those described above.

6.2 All-optical path exchange switch

We also developed a path exchange switch controlled by optical input. This kind of switch could be an important device for future all-optical routing systems. The experimental setup and results are shown in **Fig. 10**. The switch requires only a simple ring resonator with two resonant wavelengths, for example, 1554.66 nm for the pump light and 1536.54 nm for the probe light. First, we coupled the probe light to the ring resonator and propagated it to the drop port. When intense pump light was injected into the waveguide and coupled to the ring resonator, carriers were induced in the ring through a two-photon absorption effect. The carriers modified the effective refractive index of the resonator, which changed the resonant frequency. As a result, the probe light could not resonate and propagate to the drop port, so it exited via the through port. Thus, the pump light controlled the path of the probe light.

6.3 Wavelength converters using four-wave mixing

All-optical wavelength conversion may be an important technique in future all-optical routing systems. Although wavelength converters based on optical-to-electrical (O/E) and electrical-to-optical (E/O) techniques provide good signal quality, all-optical wavelength converters offer the advantages of modulation-format and bit-rate transparency and simultaneous conversion of multiple wavelengths. Generally, nonlinear effects in Si crystal are far weaker than in III-V semiconductors and nonlinear optical crystals. However, since even a 15-dBm laser can produce a power density of 100 MW/cm^2 in a Si-wire wave-

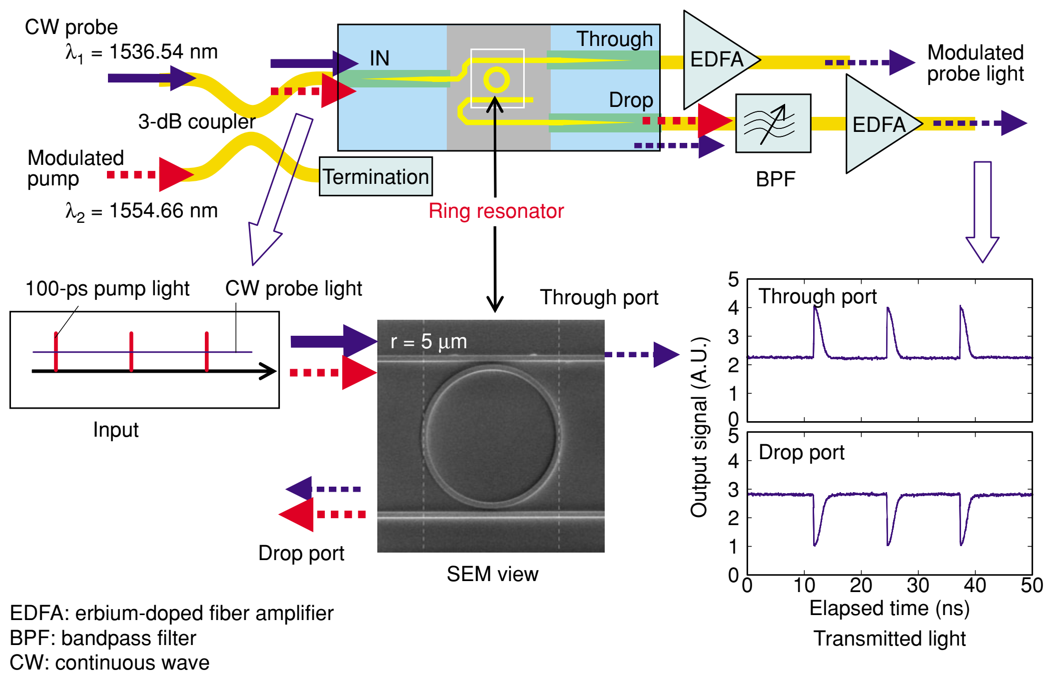


Fig. 10. All-optical path routing switch.

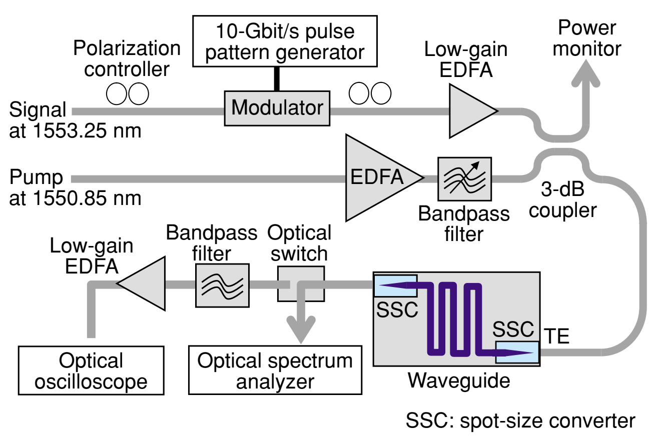


Fig. 11. Setup for wavelength conversion using the FWM effect.

guide, the nonlinear effect is greatly enhanced due to the strong light confinement. Thus, we can utilize nonlinear effects in practical functional devices.

The experimental setup for wavelength conversion based on the FWM effect [14] is shown in **Fig. 11**. The signal light and pump light were coupled into the same simple Si-wire waveguides. The signal light was modulated by a 10-Gbit/s NRZ (non-return-to-zero) data stream. The pump was operated in CW (continuous-wave) mode. The peak power of the signal input was about 5 mW. The pump input was 160 mW CW. Both lights were adjusted to TE polarization and injected into a 2.8-cm-long Si-wire waveguide. The power density in the waveguide was around 430 MW/cm^2. The output spectrum at the waveguide exit is shown in **Fig. 12**. The peak of the converted light is obvious. The fine structures in the peak are side lobes for 10-Gbit/s modulation. Conversion efficiency, defined as the peak level ratio between the signal and converted lights, was about –10.6 dB. This conversion efficiency is large enough for practical data processing. The eye diagram shows that good eye opening was easily obtained for a 10-Gbit/s PRBS (pseudo-random binary sequence) data stream of converted light. At present, the main limit on conversion efficiency is the propagation loss of the

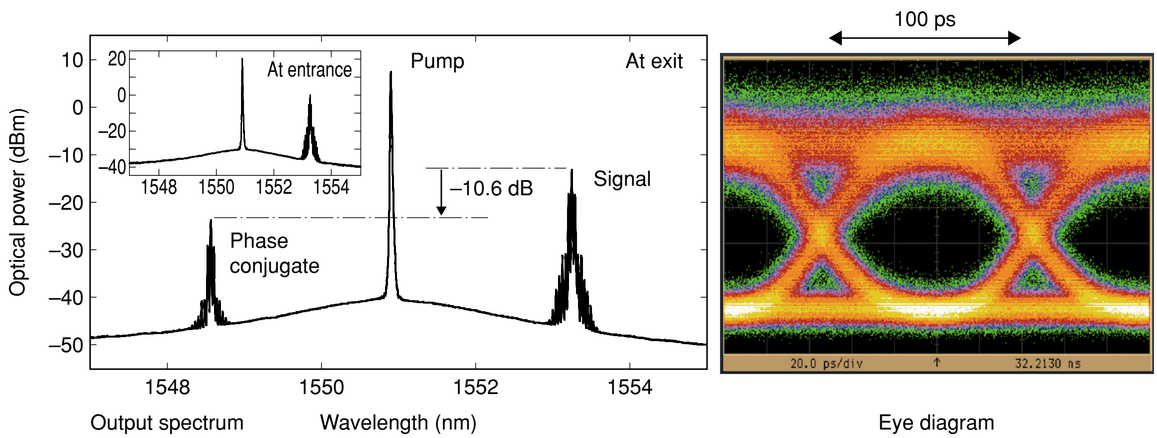


Fig. 12. Results of a FWM -based wavelength conversion experiment.

waveguide.

7. Conclusion

We demonstrated the feasibility of a Si-wire waveguide. Using Si microfabrication technologies that we improved for optical waveguides, we were able to make waveguides with very smooth sidewalls, very accurate dimensions, and low-reflection spot-size converters. By reducing the propagation and coupling losses, we were able to make extremely small photonic devices with excellent characteristics. We also confirmed active optical functions in a simple Si-wire waveguide. We note that the nonlinear effects were enhanced and carriers were created in the Si-wire waveguide. These added dynamic functions to photonic circuits. Thus, various electrically or optically controlled functional devices, such as fast optical modulators and switches, can be constructed. We should also emphasize that the most important feature of Si-wire waveguides is their applicability to electronic-photonic convergence. These photonic devices can be integrated on a common substrate with electronic devices, such as power drivers for optical modulators, amplifiers for photodetectors [15], and various sophisticated CMOS (complementary metal oxide semiconductor) logic circuits. This convergence should create a revolution in micro-devices. In addition, mass producibility is another great advantage of Si-based photonic devices. The remaining important problem in photonic circuits based on Si-wire waveguides is polarization dependence; however, it should be possible to eliminate this problem by using waveguides with square cores or by using polarization diversity systems [16]. Applying a large polarization dependence to a Si-wire waveguide should make it possible to construct a compact polarization diversity system. We believe that the Si-wire waveguide is one of the most promising platforms for highly functional, low-cost photonic circuits for future telecommunications systems.

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Seiichi Itabashi

Senior Research Engineer, Supervisor, NTT Microsystem Integration Laboratories.

He received the B.S. and M.S. degrees in physics from Tohoku University, Miyagi in 1982 and 1984, respectively and the Ph.D. degree from Hokkaido University, Hokkaido in 1998. After joining Nippon Telegraph and Telephone Public Corporation (now NTT) in 1984, he performed experimental studies on X-ray and EUV sources. He also conducted theoretical and experimental studies on highly refractive X-ray mirrors and multilayers. He is currently studying silicon-based microphotonic devices. He is a member of the Japan Society of Applied Physics (JSAP).

Hiroshi Fukuda

Research Engineer, NTT Microsystem Integration Laboratories.

He received the B.E. and M.E. degrees in nuclear engineering from Tohoku University, Miyagi in 1993 and 1995, respectively. After joining NTT in 1995, he studied electro-optical devices for communication and other applications. He is currently engaged in studies on silicon-based microphotonic devices. He is a member of JSAP and the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

Tai Tsuchizawa

Senior Research Engineer, NTT Microsystem Integration Laboratories.

He received the B.E. and M.E. degrees in physics from Sophia University, Tokyo in 1984 and 1986, respectively and the Ph.D. degree in pure and applied sciences from the University of Tokyo, Tokyo in 1990. After joining NTT Laboratories in 1990, he engaged in research on etching processes and equipment for microfabrication. He is currently studying fabrication technology for silicon-based microphotonic devices. He is a member of JSAP.

Toshifumi Watanabe

Senior Research Engineer, NTT Microsystem Integration Laboratories.

He received the B.S. and M.S. degrees in applied physics from Tokyo Institute of Technology, Tokyo in 1982 and 1984, respectively. After joining Nippon Telegraph and Telephone Public Corporation (now NTT) in 1984, he engaged in layout processing studies for electron beam pattern writers and CAD data modulation for LSI and photonic circuits. His recent interests include robust processing algorithms for very complex pattern layouts. He is a member of JSAP.

Koji Yamada

Senior Research Engineer, Distinguished Technical Member, NTT Microsystem Integration Laboratories.

He received the B.S., M.S., and Ph.D. degrees in nuclear engineering from Kyushu University, Fukuoka in 1986, 1988, and 2003, respectively. Since joining NTT Laboratories in 1988, he has engaged in theoretical and experimental studies on electron beam dynamics in synchrotrons, studies on the electromagnetic interaction between relativistic electrons and nanoscale multilayer structures, and studies of the electromagnetic properties of photonic crystals and various dielectric waveguide structures. He is a member of the Physical Sciety of Japan, JSAP, the Atomic Energy Society of Japan, the Particle Accelerator Society of Japan, and IEICE.