Optical Components and Devices for Next-Generation Photonic Networks



In this paper, we describe optical component and device technologies we have developed for next-generation photonic networks that achieve high tunability, high-speed transmission, and low power consumption. These include three-dimensional optical MEMS switches, acousto-opic tunable filters (AOTFs), lithium niobate optical modulators, and semiconductor lasers and optical amplifiers.

1. Introduction

Use of broadband access services such as asymmetric digital subscriber line (ADSL) and fiber to the home (FTTH) is rapidly growing. Current large-capacity services enable information such as high-density video to be accessed over networks. In the near future, ubiquitous services will enable us to obtain many kinds of information according to our situation and use information technology equipment (ITE), including consumer electronics, regardless of the distance between the ITE and us.

Because of changes in communication services, networks now have to cope with many types of traffic, ranging from small E-mails to large video streams. To realize effective and reliable accommodation of such traffic, next-generation photonic networks require flexible optical path connections in addition to conventional point-to-point connections between routers.

For flexible optical path connections, the tunability of optical path-switching modules, tunable optical wavelength filters modules, and other components has become one of the most important issues in optical component research and development. Because of increases in traffic, conventional requirements such as large capacity, small size, and low power consumption continue to be important in the high-packagedensity optical interfaces of optical transmission equipment. In this paper, we describe our optical component and device technologies for fabricating tunable optical modules; high-speed, low power consumption optical modules; and small-size, low power consumption optical semiconductor devices.

2. Optical modules for tunability

2.1 Optical switches: MEMS

Micro electro-mechanical systems (MEMS) based 3D optical switches have the great advantage of enabling a large number of input and output ports with a low insertion loss. We have developed the following techniques for MEMS optical switches.

Comb-driven MEMS mirrors¹⁾ have 1000 times the electrostatic force of conventional planer type electrodes, which enables a faster response and lower drive voltage. They use V-shaped torsion bars to prevent the comb teeth electrodes from sticking to each other due to "pull-in" phenomena. **Figure 1** shows a schematic of a dual-axis comb-driven MEMS mirror we have developed.

The main issue regarding the 3D-MEMS



Figure 1 Comb-driven MEMS mirror.

optical switch fabric is how to simplify its complex, three-dimensional structure while maintaining its precise alignment. To this end, we proposed a folded optical switch fabric configuration with a roof type retro-reflector (**Figure 2**).²⁾

Mechanical resonance is inevitable in MEMS mirrors, and it must be strongly suppressed in optical switches. We therefore developed a novel MEMS mirror controller.³⁾ Digital notch filters are a very efficient way to suppress this resonance, but their gate size and power consumption become excessive in large-scale switches. To solve this problem, we developed a novel digital notch filter that is time-divided by multiple channels. By using this filter, we suppressed the resonance and reduced the power consumption to 1/16 that of individual filters.

Figure 3 (a) shows an 80×80 optical switch module we fabricated by applying these techniques. This module consists of a 3D-MEMS optical switch fabric [**Figure 3 (b)**], monitor PDs, driver ICs, and a controller implemented on an FPGA. By applying the folded optical switch fabric configuration, we achieved a small module size (430 mm [W] × 400 mm [D] × 131 mm [H]) and a low insertion loss. **Figure 4** shows the insertion loss distribution measured in 80 × 80 paths. We obtained an average loss of 2.6 dB. **Figure 5**



Figure 2 Optical switch fabric configuration.

shows optical waveforms of the switching response, both with and without a time-divided digital notch filter. As can be seen, the digital notch filter sufficiently suppressed the mechanical switching resonance of the MEMS mirror. As a result, we achieved a fast switching time of 1 ms.

These results indicate this optical switch module is very advantageous for use in optical cross- connect (OXC) systems.

2.2 Wavelength tunable optical filter: AOTF

Acousto-optic tunable filters (AOTFs) are based on the wavelength selectivity of transverse electric/transverse magnetic (TE/TM) mode conversion resulting from acousto-optic effects between surface acoustic waves (SAWs) and light. The wavelength is selected by changing the RF frequency used to generate the SAW. AOTFs are very attractive devices for WDM systems because they can be switched in as little as 10 μ s and can be tuned over both the C-band and L-band. AOTFs can also simplify the architecture of optical add/ drop multiplexers (OADMs). Several OADMs with 100 GHz channel-spacing using AOTFs have been demonstrated,^{4),5)} and recently a compact photonic-gateway for dynamic path-controlling Metro



(a) 80×80 optical switch module



(b) 3D-MEMS optical switch fabric

Figure 3 80×80 optical switch module.



Figure 4 Distribution of measured insertion loss.



Figure 5 Optical switching waveform without (a) and with (b) time-divided digital notch filter.

Access Networks has been reported.⁶⁾ Because the waveguides of AOTFs are fabricated on a substrate using thin-film technology, it is easy to produce devices that integrate multiple AOTFs. **Figure 6** shows a compact $160 \times 22 \times 10$ mm module that integrates four AOTFs on a chip.

To adopt AOTFs for WDM systems, sidelobe levels in the filter characteristics have to be suppressed. Apodization methods using SAW guides have already been proposed to reduce sidelobe levels. However, we have proposed and demonstrated a novel apodization method.

Figure 7 (a) shows a schematic of an AOTF with a new type of SAW guide.⁷⁾ This device has a SAW guide with two thin-film striplines formed on a lithium niobate (LiNbO₃, LN) substrate containing two optical waveguides. The SAW field formed by the two striplines has two peaks near the striplines [**Figure 7 (b)** and **Figure 7 (c)**]. The SAW intensity in each optical waveguide changes with the distance between each stripline and each optical waveguide. By modifying the gap and width of the two striplines, arbitrary apodization can be realized to suppress the sidelobe levels.

This SAW guide is suitable for a polarizationindependent AOTF that uses polarizationdiversity optical waveguides. The symmetrical structure of this device prevents polarization dependency induced by the mechanical stress that



Figure 6 Four-channel array AOTF module.

disturbs the uniformity of birefringence. Another advantage is that apodization does not depend on the selected AOTF wavelength. This means that the filter characteristics such as the sidelobe levels and the bandwidth do not change, even though the AOTF selects different wavelengths.

Figure 8 shows a double-stage AOTF cascade we fabricated that uses the new SAW guide and the cascade's measured filter characteristics. This is the first AOTF cascade that uses Hamming apodization to suppress sidelobe levels. The sidelobe levels of this AOTF cascade are less than -35 dB from 1510 to 1610 nm for both TE and TM inputs. Its bandwidth is 0.5 nm, and its insertion loss is 3.3 dB. This is the first reported double-stage AOTF to achieve both a narrow bandwidth of 0.5 nm and sidelobe levels below -35 dB.



(a) Schematic diagram of an AOTF with a new SAW guide.



(b) Cross-section at A-A' line of (a)



(c) Cross-section at B-B' line of (a)

Figure 7 AOTF with new SAW guide and SAW fields.



Figure 8

Fabricated AOTF (a) and measured filter characteristics (b), (c).

3. Optical modules for highspeed transmission

Optical modulators with a low drive voltage reduce the cost, size, and power consumption of transmitter modules and therefore enable 40 Gb/s systems to be installed more easily. Because existing 40 Gb/s modulators require a drive voltage of about 5 V for single-drive and 3 V for dual-drive, driver amplifiers with a large output voltage are needed. We therefore decreased the drive voltage by optimizing the electrodes of a dual-drive modulator⁸⁾ as shown in **Figure 9**. The modulator contains optical waveguides consisting of a Mach-Zehnder (MZ) optical interferometer, coplanar waveguide (CPW) electrodes on each MZ arm, and a buffer layer between them to reduce the optical loss due to the electrodes. Here, S, L, and t indicate, respectively, the gap between the CPW signal electrodes and ground electrodes, the interaction length between the electrodes and optical waveguides, and the thickness of the electrodes.

Forty-Gb/s optical modulators require an electrical-to-optical (E/O) bandwidth of over 30 GHz. However, there is a tradeoff between the E/O bandwidth and drive voltage, both of which depend on the parameters of the CPW electrodes. Conventionally, CPW electrodes with a narrow gap and short interaction length have been used, resulting in a drive voltage of 5 V with single-electrode driving.^{9),10)} We decided to improve the characteristics of the 40 Gb/s modulator by optimizing its electrode design.

We investigated the gap dependency of microwave loss in relation to the electric bandwidth, half-wave voltage $V\pi$, and interaction length L of MZ modulators. The general understanding is that, to enable a reduction in drive voltage, the gap of CPW electrode S should be decreased in order to increase the electric field applied to the optical waveguides [Figure 10 (a)]. However, our calculations indicate that if we instead increase the gap of electrode S, the lower microwave loss enables L to be increased and $V\pi$ to be decreased [Figure 10 (b)]. When the gap is decreased, on the other hand, an electrical bandwidth of 30 GHz can only be achieved with a higher $V\pi$. This is because L must be decreased to prevent an increase of the microwave loss. We found that an electrode with a wide gap and long interaction length was more effective for decreasing the drive voltage for 40 Gb/s modulation.

We fabricated a dual-drive modulator having a novel wide-gap, long-L electrode. The optical fiber-to-fiber insertion loss of this modulator is 6 dB, and its extinction ratio is 27 dB. These val-



Figure 9

Dual-drive Mach-Zehnder modulator: (a) top view (b) oblique view. S, L, and t indicate gap, interaction length, and thickness of electrode, respectively.







ues are suitable for practical use. The 3 dB E/O bandwidth of the optical response is 28 GHz. **Figure 11** shows the 40 Gb/s eye diagrams for the driving signal and optical output in a 2^{31} -1 Pseudo Random Bit Sequence (PRBS). Clear eye openings were obtained with a very low drive voltage of 0.9 V.

4. Optical semiconductor devices

4.1 Quantum-dot lasers

The quantum dot is a three-dimensional nanostructure. In a quantum dot, due to its very small size, carriers such as electrons and holes only occupy discrete energy states — this is quite



Figure 11

Eye diagram at 40 Gb/s of fabricated low-drive-voltage modulator.

different from the case in quantum wells, which used in commercially-available are now semiconductor lasers. Because of this feature, semiconductor lasers with quantum-dot active layers have unique and attractive characteristics, for example, a low threshold current, reduced temperature sensitivity, and small wavelength chirping under modulation. Since the early 90s, we have studied crystal growth technology for quantum dots and have recently, in cooperative research with the University of Tokyo, fabricated 1.3 µm-wavelength quantum-dot lasers with drastically reduced temperature sensitivity for 10 Gb/s operation.¹¹⁾⁻¹³⁾

Figure 12 (a) shows the structure of a fabricated quantum-dot laser. Unlike conventional 1.3 μ m-wavelength lasers, quantum-dot lasers are formed on a GaAs substrate. The active layer consists of InAs quantum dots sandwiched between GaAs barrier layers. We used 10 layers of quantum dots to obtain sufficient gain for 10 Gb/s operation and introduced p-type doping in the center part of the GaAs barrier layers to suppress temperature sensitivity. We carefully designed the cavity structure with a length of 200 μ m and a highly reflective (HR) coating (81%) on both facets to achieve a low operating current and a large modulation bandwidth.

As shown in Figure 12 (b), the fabricated

quantum-dot laser provided temperature-stable light-current characteristics. The threshold current was as low as 2.2 mA at 20°C, and we obtained almost constant characteristics between 20 and 50°C. From measurements of the frequency response, we also confirmed that the temperature sensitivity of the modulation bandwidth was reduced. **Figure 12 (c)** shows the 10.31 Gb/s eye diagram at 25 and 90°C. For both temperatures, the bias current was 30 mA and the modulation current was 35 mA_{pp} . The dynamic extinction ratios were 6.8 and 7.3 dB at 25 and 90°C, respectively. Thanks to the temperature-stable characteristics of the quantum-dot laser, we obtained almost the same eye diagrams over a wide temperature range, even under fixed driving. Using this laser and an optical receiver with an electric dispersion compensator, we performed a transmission experiment using multimode fiber (MMF) with a 50 µm-core diameter and successfully achieved error-free transmission through 300 m of MMF between 25 and 80°C. These results indicate that the quantum-dot laser is a promising light-source for future low-cost transmitters in optical local area networks.

4.2 SOAs

In future photonic networks, semiconductor optical amplifiers (SOAs) will play key roles as



Figure 12

 $1.3~\mu\text{m}\text{-wavelength}$ quantum dot laser: structure and characteristics.

low-cost optical amplifiers, optical gate switches, and all-optical signal-processing devices. The advantages of SOAs are their compactness, potentially low cost, wide gain-bandwidth, and monolithic integratibility. In linear amplification of optical signals modulated in the gigabitper-second range, a high saturation output power is essential to avoid waveform distortion due to the pattern effect. Polarization-insensitive gain is also required if SOAs are to be used as widely as in-line optical amplifiers. We therefore developed a 1550 nm high-saturation output power, polarization-insensitive SOA by using a tensilestrained barrier multi-quantum well (MQW) active layer.¹⁴⁾

Figure 13 shows the structure of the SOA. An active layer only 45 nm thick was used to achieve a high saturation output power. In the active layer with the flat rectangular crosssection, the optical confinement for the TE mode is larger than that for the TM mode. To achieve polarization insensitive gain, the difference in the optical confinement factor between the two modes must be compensated for by the difference in the optical gains of the two modes. We therefore used an MQW structure with lattice-matched GaInAs wells and tensile-strained GaInAs barriers as an active layer to increase the optical gain for the TM mode. The SOA chip is 0.9 mm long. The input and output sides of the SOA both have a width-tapered spot-size converter (SSC) to

improve the chip-fiber coupling. The waveguide is tilted 7 degrees, and both facets are AR coated to reduce the facet reflectivity.

The SOA chip was packaged into a module with high numerical aperture lenses, polarization insensitive isolators, second lenses, and singlemode fibers. The optical coupling loss between the SOA chip and the fiber was estimated to be about 2 dB per facet. **Figure 14** shows the gain saturation characteristics of the SOA module under continuous wave (CW) operation at 1550 nm for the TE and TM modes. An unsaturated gain of 10.4 dB and a polarization sensitivity of 0.6 dB were obtained. The saturation output power was larger than +20 dBm, and the noise figure (NF) was 6.0 dB. To our best knowledge, compared to reported polarization-insensitive SOAs, this device has the highest saturation output power and an NF comparable to the lowest record. Figure 15 shows the gain-current characteristics of the SOA module in the TE mode. The input signal power was -20 dBm. An on-off ratio of more than 65 dB was obtained by switching the injection current between 0.1 and 300 mA. This very large on-off ratio makes the SOA attractive for use in optical gate switches because it enables an extremely low crosstalk to be realized.



Figure 13 Structure of tensile-strained barrier MQW SOA.



Figure 14 Gain saturation characteristics of SOA module.



Figure 15 Gain current characteristics of SOA module.

5. Conclusion

In this paper, we described our optical component and device technologies for achieving high tunability, small size, and low power consumption. Our technologies will contribute to the evolution of photonic networks.

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References

- Y. Mizuno et al.: A 2-Axis Comb-Driven Micromirror Array for 3D MEMS Switches. IEEE/LEOS Int. Conf. on Optical MEMS (Optical MEMS 2002), Lugano, Switzerland, Aug. 2002, p.17-18.
- T. Akashi et al.: Low-loss 80 × 80 3D-MEMS Optical Switch Module Fabricated with a Simple Alignment Technique. Int. Topical Meeting on Photonics in Switching (PS2002), WeA2, Cheju, Korea, July 2002, p.107-109.

- S. Ide et al.: High-Speed 80 × 80 MEMS Optical Switch Module with VOA. ECOC-IOOC 2003 Vol.1, 2003, p.30-33.
- T. Nakazawa, M. Doi, S. Taniguchi, Y. Takasu, and M. Seino: Ti:LiNbO₃ AOTF for 0.8 nm Channel-Spaced WDM. Optical Fiber Communication Conference '98, PD-1, 1998.
- 5) H. Miyata, Y. Kaito, Y. Kai, H. Onaka, T. Nakazawa, M. Doi, M. Seino, T. Chikama, Y. Kotaki, K. Wakao, M. Komiyama, T. Kunikane, H. Yonetani, and Y. Sakai: Fully dynamic and reconfigurable optical add/drop multiplexer on 0.8 nm channel spacing using AOTF and 32-wave tunable LD module. Optical Fiber Communication Conference, 2000 Volume 4, PD40, 2000, p.287-289.
- 6) G. Nakagawa, Y. Kai, K. Sone, Y. Takita, K. Miyazaki, T. Ueno, M. Noguchi, H. Miyata, H. Miyata, and H. Onaka: Compact Photonic-Gateway for Dynamically Path-controlling Metro Access λ -Networks. Opto-Electronics and Communications Conference (OECC) 2005, 5B2-4, 2005.
- 7) H. Miyata, T. Uematsu, and K. Tanaka: Low Sidelobe AOTF with a New SAW Guide. Opto-Electronics and Communications Conference (OECC) 2006, 5B4-2, 2006.
- 8) M. Sugiyama, M. Doi, S. Taniguchi, T. Nakazawa, and H. Onaka: Driver-less 40 Gb/s LiNbO₃ modulator with sub-1 V drive voltage. Optical Fiber Communication Conference and Exhibit 2002, Postdeadline paper FB6-1, Mar. 2002.
- O. Mitomi, K. Noguchi, and H. Miyazawa: Broadband and low driving-voltage LiNbO₃ optical modulators. *IEE Proceedings - Optoelectronics*, 45, 6, 1998, p.360-364.
- 10) M. M. Howerton, R. P. Moeller, A. S. Greenblatt, and R. Krahenbuhl: Fully packaged, broad-band LiNbO₃ modulator with low drive voltage. *IEEE Photon. Technol. Lett.*, **12**, 7, p.792-794 (2000).
- M. Sugawara et al.: Recent progress in selfassembled quantum-dot optical devices for optical telecommunication: temperature-insensitive 10 Gb s⁻¹ directly modulated lasers and 40 Gb s⁻¹ signal-regenerative amplifiers. *J. Physics D*, **38**, 13, p.2126-2134 (2005).
- 12) T. Yamabana et al.: Temperature independent transmission for 10 Gbps 300m-MMF using low driving-current quantum dot laser. Optical Fiber Communication Conference (OFC2006), OFL3, Anaheim, USA, March 2006.
- 13) M. Ishida et al.: Low-driving-current 10 Gb/s direct modulation of temperature-stable $1.3 \,\mu m$ p-doped quantum-dot lasers between 20°C and 90°C. Conference on Lasers and Electro-Optics (CLEO2006), CTHGG5, Long Beach, USA, May 2006.
- 14) S. Tanaka, S. Tomabechi, M. Ekawa, and K. Morito: A High Saturation Output Power (+22 dBm) Polarization Insensitive Semiconductor Optical Amplifier. 2005 IEEE LEOS Annual Meeting, Sydney, 2005, ThK5.



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