High-speed Switching Operation in a Thermocapillarity Optical Switch for Application to Photonic Networks

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Abstract

We have improved our previously developed waveguide optical switch called Olive (oil-latching interfacial-tension variation effect switch) by developing basic technologies for lowering the viscosity of the refractive-index-matching liquid and shortening the distance the liquid must travel. In combination with our previously developed highly accurate deep-groove fabrication with a high aspect ratio, batch injection of a very small amount of liquid, and high-performance sealing, these improvements enabled us to achieve a switching time of less than 10 ms while maintaining excellent optical characteristics. This switching time, which is about one-tenth that of our previous Olive, breaks through an important threshold, allowing Olives to be used for optical crossconnects and add/drop multiplexers.

1. Introduction

Optical switches are key components for the sophisticated optical processing systems required for optical add/drop multiplexers (OADM), optical crossconnects (OXC), and standby optical system of photonic networks [1]-[3]. They should be self-latching (i.e., they must retain each state without power being supplied) and must be have excellent optical characteristics (low insertion loss, high extinction ratio, low crosstalk, polarization, and wavelength insensitivity) in addition to fast switching and high reliability. They must also be compact to allow high-density integration and be inexpensive [4], [5].

We previously developed a silica-based waveguide optical switch called the oil-latching interfacial-tension variation effect switch (Olive) [6]. It is self-latching and exhibited low insertion loss (below 3 dB in a 1×8 optical switch), high extinction ratio (>50 dB), low crosstalk (<–50 dB), and wavelength insensitivity (±0.5 µm). The switch chip size is about 10×10 mm [7]. However, its switching time of 50–100 ms is rather slow for OADMs and OXCs, though it would be suitable as the optical switch for standby optical systems and reconfiguration systems [8]. OADMs and OXCs require a switching time on the order of 1 ms [4]. Achieving such fast switching would greatly expand the applicability of Olive.

This paper introduces basic technologies that successfully enabled us to reduce the switching time to 1/10 and describes the optical characteristics of a fabricated switch.

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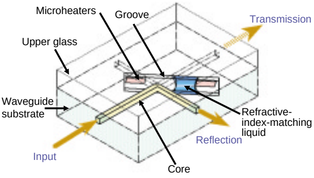
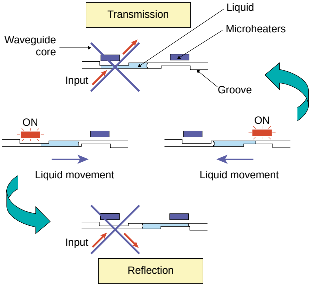
2. Structure and operation principle of Olive

Figure 1(a) shows the basic structure of our switch. It is a waveguide optical switch with a microactuator fabricated in a planar lightwave circuit (PLC) by micromachining. It consists of an upper glass substrate and an intersecting waveguide substrate that has a groove at each crossing point and a pair of microheaters. The groove is partially filled with refractive-index-matching liquid and is completely sealed by the upper glass substrate.

When the liquid is present at the crossing point of waveguides, the optical signals pass straight through the groove. On the other hand, when the liquid moves away from the crossing point leaving it filled with air, the optical signals are switched into the crossing waveguide by total internal reflection [9] on the



(a) Basic structure



(b) Basic concept of optical switching

Fig. 1. Structure and switching operation of an Olive.

groove wall, i.e., at the silica-air interface.

Figure 1(b) shows the basic switching concept. The interfacial tension of the air-liquid interface is decreased by heating (thermocapillarity). This allows the liquid in the groove to move toward the opposite side of the groove. The liquid is held there by the capillary pressure, which is determined by the groove width. These two phenomena in combination provide the switching operation and self-latching function.

3. Basic technologies for improving the switching time

3.1 Considerations

The switching time is expressed in terms of the groove structure (groove width, groove depth, distance traveled by the liquid) and liquid characteristics (absolute viscosity of the liquid and surface tension difference at the liquid column during heating) (Fig. 2). When the liquid flow is approximated as the steady-state flow of viscous fluid, the switching time t is described by [10]

$$t \propto \mu \cdot 1/d \cdot w\Delta\gamma, \qquad (1)$$

where w is the groove width, d is the groove depth, l is the travel distance of the liquid, μ is the absolute viscosity of the liquid, and γ is the surface tension difference at the liquid column in heating. To improve the switching speed, we decided to lower the viscosity of the liquid and shorten the liquid's travel distance. There is no trade-off between these approaches, so by doing both, we should shorten the switching time substantially.

3.2 Lowering the viscosity of refractive-index-matching liquid [10]

The refractive-index-matching liquid should have low viscosity, low volatility, good refractive-index controllability, and high thermal and chemical stability. To satisfy these requirements, we developed a new liquid composed of a single substance based on

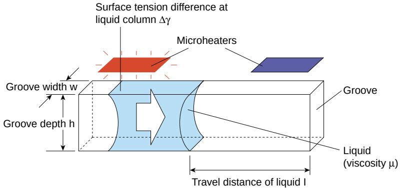


Fig. 2. Parameters related to improvement of switching time.

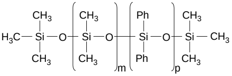


Fig. 3. Chemical structure of dimethyldiphenylpolysiloxane.

dimethyldiphenylpolysiloxane (Fig. 3).

It is well known that the viscosity of a liquid can be represented as a function of its weight-average molecular weight as shown in Fig. 4. In this figure, the red circle indicates the previous liquid, which had a viscosity of 50 centipoise (cP) and weight-average molecular weight of about 3000. To obtain a liquid with viscosity of 10 cP, we should abstract the weight-average molecular weight of about 1000 in dimethyldiphenylpolysiloxane. By using the gel chromatography method instead of the distilling method, we were able to achieve the target viscosity of 10 cP, which is one-fifth that of the previous liquid, without any refractive index mismatch or thermal stability degradation.

A refractive index of 1.449 at 25°C can be obtained by adjusting both the dimethyl and diphenyl contents in dimethyldiphenylpolysiloxane. We also found that the new liquid has suitable thermal stability (heat decomposition temperature is about 230°C) and low volatility (comparable with the previous liquid).

3.3 Shortening the travel distance of the liquid

Figure 5 shows the parameters related to shortening the travel distance of the liquid. L is the groove length, l is the travel distance of the liquid, x is the length of the liquid column, and d is the margin length of the liquid column. The ideal case, i.e., having no margin, is L=l+x.

We designed the fundamental structure so as to shorten the travel distance of the liquid without affecting the liquid column length at which effective TIR is generated and to maintain the liquid margin length needed for latching.

It should be mentioned here that we achieved high liquid injection accuracy through high uniformity processing of the sizes of both the groove and liquid injection slit. The tolerance for the amount of injected liquid decreased from ±10% to ±5%.

As a result of the newly designed fundamental structure and accurate liquid injection, we were able

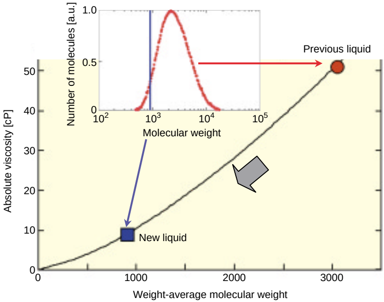


Fig. 4. Relationship between absolute viscosity and weight-average molecular weight.

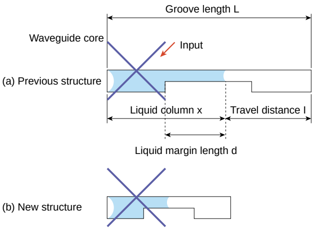


Fig. 5. Parameters related to shortening the liquid's travel distance.

to reduce the travel distance from 120 to 60 µm in a prototype Olive.

4. Fundamental characteristics of the improved Olive

4.1 Switching speed and optical characteristics

We fabricated a prototype 16-channel 2×2 Olive (Fig. 6) using the above-mentioned technologies and examined its optical characteristics. Figure 7 shows the transient optical waveform of the old and new Olives. In the old one, the viscosity of the liquid was 50 cP and the travel distance about 120 µm. In the new one, those values are 10 cP and about 60 µm. Both switches operate at a driving power of 0.15 W and heating duration of 4 ms. The switching time of the new Olive is only 6 ms, which is about 1/10 that of our previous Olive. This switching time is comparable to that of MEMS (micro–electro–mechanical systems) switches and other waveguide optical switches. Table 1 summarizes the characteristics of the old and new Olives. The optical characteristics of the new Olive are the same as those of the previous one except for the switching speed.

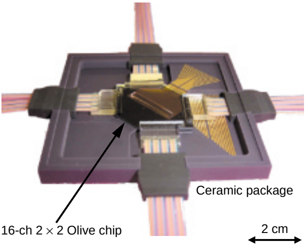


Fig. 6. Appearance of the fabricated 16-channel 2 × 2 Olive.

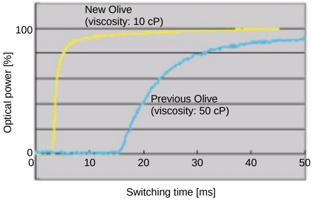


Fig. 7. Transient optical waveforms of previous and new Olives.

Table 1. Characteristics of previous and new Olives.

	Previous	New
Transmission loss (dB)	0.12	
Reflection loss (dB)	1.2	
Crosstalk (dB)	< –50 (0 to 40°C)	
Driving power (W)	0.15	
Switching time (ms)	50	6

4.2 Reliability

The reliability test for the new Olive was performed in accordance with the Telcordia standard (GR-1221-core etc.). We tested heat shock, high temperature and high humidity, storage at high temperature, storage at low temperature, heat cycles at high humidity, shock, vibration, and continuous switching.

In the heat shock test (–15°C to 85°C, 20 cycles), we did not observe any significant change in liquid column length before and after the test. This confirmed the perfect liquid seal in the Olive. In the high temperature and high humidity test (85°C, 85% RH), we did not observe any significant degradation of the optical characteristics, such as the insertion loss or crosstalk even after 2000 hours. The insertion loss fluctuation was less than ±0.5 dB. From these results, it is clear that the epoxy resin for the liquid sealing and connection between optical fibers and an Olive did not degrade. The continuous switching test indicated that more than 20 million switching operations can be achieved without any significant degradation of the optical characteristics. So far, we have not discovered any critical problems in the reliability tests, indicating that the new Olive has sufficient reliability for practical use.

5. Applications to optical transmission systems

5.1 Fundamental performance [11]

An Olive must offer not only high-speed (<20 ms) operation but also high transmission performance for practical implementation of OADMs or OXC modules. Since the improved switching time (<10 ms) satisfies the former requirements, we discuss transmission performance in this section.

We focused on the coherent crosstalk noise generated at every intersection of the waveguides due to the superposition of transmitted signals, which may cause more significant signal-to-noise ratio (SNR) degradation than power fluctuations do. To investigate this possibility, we performed transmission experiments using two independent optical signals modulated at 10 Gbit/s in NRZ (non-return to zero) format.

Figure 8 shows the measured transmission performance when one signal collides with another signal at an intersection. The resulting bit error rate versus signal power indicates error-free performance. The temporal waveform shows clear eye opening. Considering that the intrinsic channel crosstalk due to undesirable diffraction at intersections is around 45 dB, the Olive can be used in practical optical transmission systems.

5.2 Implementation in systems [11]

Scalability is a key function for next-generation data communications and telecommunications systems based on photonic networks. Olives can contribute to the construction of such networks due to their self-latching, thereby providing low-power operations under remote control via command instructions. We fabricated an OADM using a 1×n Olive with wavelength-tunable optical modules to demonstrate the merits of the Olive. Figure 9 shows a schematic diagram of the OADM, which expands the multiplexed optical signals to be manipulated in the Fourier space between the two arrayed waveguide gratings (AWG) modules and performs add/drop operation for arbitrary channels. By using the Olive, we have successfully fabricated a compact OADM frame (Fig. 10). We plan to improve such modules to handle a larger number of wavelength division multiplexing (WDM) channels as required in future net-

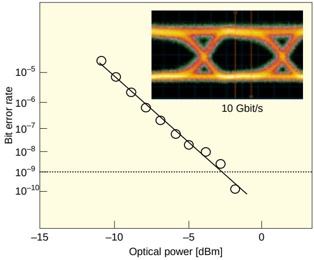


Fig. 8. Transmission performance.

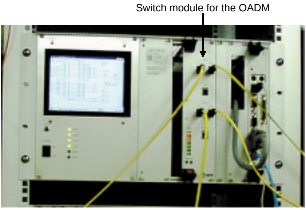


Fig. 10. Appearance of the switch module in the OADM sub-system.

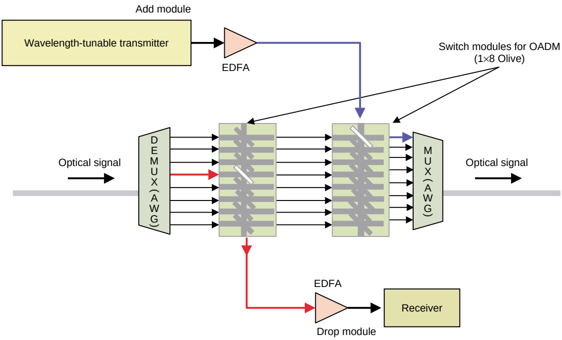


Fig. 9. Schematic diagram of the OADM.

works.

6. Conclusions

By developing basic technologies, we have made a high-performance oil-latching interfacial-tension variation effect switch (Olive) with millisecond-order switching speed. This is fast enough to be used as the optical switch in OADM and OXC systems, which will greatly increase the applicability of the Olive.

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