# PLC-MZI-type 3-Wavelength Wideband WDM Filter Array for FTTH Video Distribution Services

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**ABSTRACT** With the rapid spread of FTTH services in recent years, there have been proposals for a broadband passive optical network (B-PON) system that combines data transmission services with simultaneous video distribution services. Taking advantage of the new wavelength assignments —1.31, 1.49 and 1.55 µm— which have become international standards under ITU-T G983.3, requires a WDM filter that is economical and of high functionality to multiplex these three wavelengths. Specifically, central offices require compact WDM modules that contain WDM filter arrays.

Accordingly we have developed an 8-channel 3-wavelenth wideband WDM filter array using a new optical circuit configuration based on a Mach-Zehnder interferometer (MZI) that uses silica-based planar lightwave circuit (PLC) technology, and have been able to obtain good performance: insertion loss of <1.96 dB, loss ripple of <0.77 dB and isolation of >32 dB.

## 1. INTRODUCTION

In recent years, as Internet connections have reached into every home, there has been widespread adoption of high-speed low-cost services including always-on connections, megabit-class transmission speeds and monthly fees of a few tens of dollars. And greater use is being made of the kind of large-volume content distribution and video chatrooms consistent with broadband connections.

To provide this type of broadband service, a broadband passive optical network (B-PON) system has been made an international standard under ITU-TG983.3, capable of delivering data transmission speeds of 100 Mbps (peak) simultaneously with up to 500-channel video distribution over a single optical fiber. Figure 1 shows the structure of a typical system [1].

The principal feature of this system is that due to new optical wavelength assignments, it permits reception of two wavelengths used for transmission of high-speed data, and, by superimposing one more optical wavelength, simultaneous distribution of multi-channel video. Ordinarily the wavelengths for high-speed data transmission and reception are the 1.49-µm band (1.48~1.50 µm) for the downstream and the 1.31-µm band (1.26~1.36 µm) for the upstream, and video data is distributed on the 1.55-µm band (1.55~1.56 µm), which is the EDFA amplification band. For this reason it is necessary to have a wavelength division multiplexing (WDM) filter to simultaneously demux the three wavelengths—the high-speed data transmission wavelengths and the video signal wavelength—on a single optical fiber. In the past there have been various candidates for this WDM filter. The most generally used type, one that adopts a dielectric multi-layer film filter, has been reported to have excellent characteristics including low loss and wideband operation [2], but to improve economy in central offices there is a need for array installations and in this respect it is not satisfactory.

In contrast, a WDM filter that adopts silica-based planar lightwave circuit (PLC) technology is promising from the standpoint of array design, and up to the present time several methods have been considered. One of these is a WDM filter with a dielectric multi-layer filter inserted at the crossing point of intersecting waveguides formed of silica-based PLC [3]. However because of the formation of the slit for filter insertion and the complexity of the processes of filter insertion and mounting, it is not satisfactory from the standpoint of economy. And in terms of characteristics, while it achieves low loss and low loss ripple, it presents a problem in terms of the characteristics of the dielectric multi-layer filter in that return port isolation, at <20 dB, is

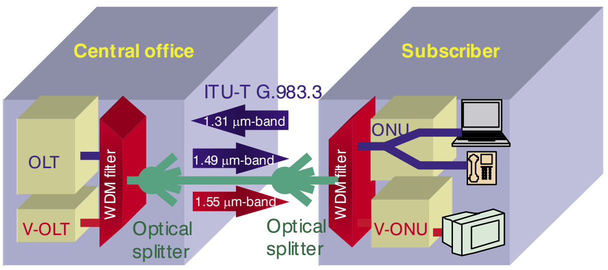


**Figure 1  Structure of typical B-PON system.**

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unsatisfactory.

Another method that has been considered is a WDM filter based on a Mach-Zehnder interferometer (MZI) [4), 5)]. Since the PLC-MZI-type WDM filter achieves its characteristics in the optical circuit only, it does not need any of the additional processing that has been described above, and is therefore generally considered to be the most suitable method in terms of economy. At the same time as offering a wider band, however, it does present problems in terms of degradation of loss ripple in the pass band and degradation of isolation in the stop band, and improvements must be made before practical characteristics can be achieved.

In this paper, accordingly, we propose a novel optical circuit based on the MZI, present details of its design, and report on the results of fabricating an 8-channel PLC-MZI-type 3-wavelenth wideband WDM filter array.

## 2. OPTICAL CIRCUIT CONFIGURATION AND DESIGN

### 2.1 Structure and Formulation of PLC-MZI-type Wideband WDM Filter

Figure 2 shows a schematic of the optical circuit configuration for the proposed PLC-MZI-type wideband WDM filter. It has a cascaded MZI consisting of four identical directional couplers and two different phase shifters, connected point-symmetrically with respect to its output waveguide.

We then proceeded to formulation of a concrete optical circuit design. First we broke down the WDM filter circuit into its component elements, as shown in Figure 3. That is to say optical coupler $S_1$ is connected in a fully point-symmetrical manner with respect to its output waveguide, and that optical coupler $S_1$ can be considered as a PLC-MZI in which optical coupler $S_3$ is connected through phase shifter $T_{\phi 1}$ in a point-symmetrical manner with respect to its output waveguide, and further, optical coupler $S_3$ consists of two identical directional couplers $S_5$ and phase shifter $T_{\phi 0}$.

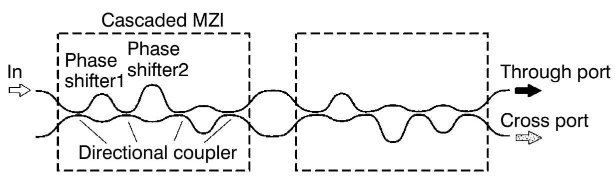



**Figure 2 Schematic optical circuit configuration for proposed PLC-MZI-type wideband WDM filter.**

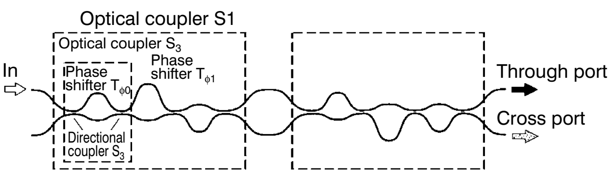



**Figure 3 Breakdown of optical circuit for PLC-MZI-type wideband WDM filter into component elements.**

First of all we carried out a formulation of a PLC-MZI-type wideband WDM filter. From Figure 3 as mentioned above, the PLC-MZI-type wideband WDM filter may be represented as in Figure 4.

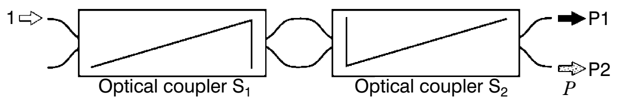



**Figure 4 Circuit arrangement for PLC-MZI-type wideband WDM filter.**

Taking the transfer matrix for the case in which optical coupler $S_1$ is connected in a fully point-symmetrical manner as

$$S_1 = \begin{pmatrix} a & -b^* \\ b & a^* \end{pmatrix}, \quad S_2 = \begin{pmatrix} a^* & -b^* \\ b & a \end{pmatrix}, \quad |a|^2 + |b|^2 = 1$$

we obtain

$$\begin{pmatrix} P_1 \\ P_2 \end{pmatrix} = S_2 \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} S_1 \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} a^* a - b^* b \\ 2ab \end{pmatrix} \qquad (1)$$

where: * designates a complex conjugate.

Accordingly the optical intensity of the cross-port, that is to say the coupling efficiency $P$ of the PLC-MZI-type wideband WDM filter, may be determined by

$$|P_2|^2 = P = |2ab|^2 = 4b^2(1-b^2) = 4\eta(1-\eta) \qquad (2)$$

where: $\eta$ is the coupling efficiency of optical coupler $S_1$.

Next, Figure 5 shows the circuit arrangement for optical coupler $S_1$.

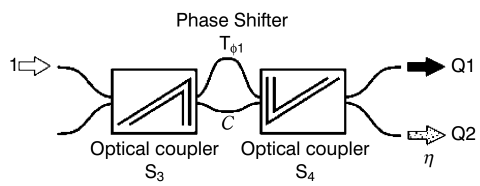



**Figure 5 Circuit arrangement for optical coupler $S_1$.**

Taking the transfer matrix for the case in which optical coupler $S_3$ is connected through phase shifter $T_{\phi 1}$ in a point-symmetrical manner as

$$S_3 = \begin{pmatrix} \alpha & -\beta^* \\ \beta & \alpha^* \end{pmatrix}, \quad S_4 = \begin{pmatrix} \alpha^* & -\beta^* \\ \beta & \alpha \end{pmatrix}, \quad |\alpha|^2 + |\beta|^2 = 1$$

and

$$T_{\phi 1} = \begin{pmatrix} e^{-j\frac{\phi_1}{2}} & 0 \\ 0 & e^{j\frac{\phi_1}{2}} \end{pmatrix}$$

we obtain

$$\begin{pmatrix} P_1 \\ P_2 \end{pmatrix} = S_4 T_{\phi 1} S_3 \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} |\alpha|^2 e^{-j\frac{\phi_1}{2}} - |\beta|^2 e^{j\frac{\phi_1}{2}} \\ 2\alpha\beta \cos\frac{\phi_1}{2} \end{pmatrix} \quad (3)$$

where: $\phi_1$ is the amount of phase shift of phase shifter $T_{\phi 1}$.

Accordingly the optical intensity of the cross-port, that is to say the coupling efficiency $\eta$ of optical coupler $S_1$, may be determined by

$$|Q_2|^2 = \eta = \left|2\alpha\beta\cos\frac{\phi_1}{2}\right|^2 = 4\beta^2(1-\beta^2)\cos^2\frac{\phi_1}{2}$$
$$= 4C(1-C)\cos^2\frac{\phi_1}{2} \quad (4)$$

where: $C$ is the coupling efficiency of optical coupler $S_3$.

Next, Figure 6 shows the circuit arrangement for optical coupler $S_3$.

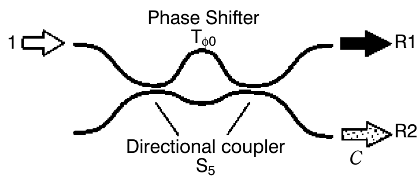



**Figure 6 Circuit arrangement for optical coupler $S_3$.**

And in the same way as above described, the optical intensity of the cross-port, that is to say the coupling efficiency $C$ of optical coupler $S_3$, may be determined by

$$|R_2|^2 = C = 4\kappa(1-\kappa)\cos^2\frac{\phi_0}{2} \quad (5)$$

where: $\kappa$ is the coupling efficiency of directional coupler $S_5$ and $\phi_0$ is the amount of phase shift of phase shifter $T_{\phi 0}$.

From the above discussion we can represent the characteristics of the PLC-MZI-type wideband WDM filter using Equations (2), (4) and (5).

### 2.2 Design of PLC-MZI-type 3-Wavelength Wideband WDM Filter

Next we proceeded to the design of a 3-wavelenth wideband WDM filter consisting of PLC-MZI wideband WDM filters.

First of all the through-port is set to output light of $\lambda$= 1.31 µm and 1.49 µm. From Equation (2) we can then obtain

$$P \approx 0 \Leftrightarrow 4\eta(1-\eta) \approx 0 \Leftrightarrow \eta \approx 0 \quad or \quad \eta \approx 1 \quad (6)$$

First let us consider the case where $\eta\approx1$. In this case it is necessary from Equation (4) to satisfy $4C(1-C)\approx1$ and $\cos^2(\phi_1/2)\approx1$ simultaneously. Now if we consider the case in which $4C(1-C)\approx0.99$ and $\cos^2(\phi_1/2)\approx0.99$, each parameter diverging from the design value by 1 %, we will get $\eta\approx0.98$, or 2 % divergent from the design value.

Next let us consider the case where $\eta\approx0$. In this case it is sufficient from Equation (4) to satisfy only one of $4C(1-C)\approx0$ or $\cos^2(\phi_1/2)\approx0$, but when they are satisfied simultaneously more stable characteristics will be obtained. For example even in a case in which $4C(1-C)\approx0.01$ and $\cos^2(\phi_1/2)\approx0.01$, each parameter diverging from the design value by 1 %, we see that we will get $\eta\approx0.0001$, virtually no divergence (only 0.01 %) from the design value. Furthermore with this effect the change in $\eta$ due to wavelength will be made slower and the band will be widened. From this we can obtain as a first condition

$$4C(1-C) \approx 0$$

and

$$\cos^2\left(\frac{\phi_1}{2}\right) \approx 0 \Leftrightarrow \phi_1 \approx (2m+1)\pi$$
$$@\lambda = 1.31\ \mu m,\ 1.49\ \mu m \quad (7)$$

Next let us consider $4C(1-C)\approx0$ in the first half of Equation (7). As in Equation (6) we can obtain $C\approx0$ or $C\approx1$, but from the above discussion we select $C\approx0$. Here, when designing a 3-wavelenth wideband WDM filter, particularly at $\lambda$=1.31 µm, a much wider band of ±50 nm is required. Accordingly in this instance, limited to $\lambda$=1.31 µm, we make settings such that $C\approx0$, and pursue band widening in that band of wavelengths. That is to say, from Equation (5), we can obtain as a second condition

$$4\kappa(1-\kappa) \approx 0$$

and

$$\cos^2\left(\frac{\phi_0}{2}\right) \approx 0 \Leftrightarrow \phi_0 \approx (2n+1)\pi$$
$$@\lambda = 1.31\ \mu m \quad (8)$$

Then from $4\kappa(1-\kappa)\approx0$ in the first half of Equation (8) we can obtain $\kappa\approx0$ or $\kappa\approx1$. In this case it does not matter which is used, but since, generally speaking, the longer the coupling length of the directional coupler becomes the more subject it is to fabrication errors, here we choose $\kappa\approx0$.

To summarize the design conditions with respect to the through-port based on the above, simultaneously satisfying

$$\left.\begin{array}{l} \cos^2\left(\frac{\phi_1}{2}\right) \approx 0 \Leftrightarrow \phi_1 \approx (2m+1)\pi \\ \quad @\lambda = 1.31\ \mu m,\ 1.49\ \mu m \\ \cos^2\left(\frac{\phi_0}{2}\right) \approx 0 \Leftrightarrow \phi_0 \approx (2n+1)\pi \\ \quad @\lambda = 1.31\ \mu m \\ \kappa \approx 0 \\ \quad @\lambda = 1.31\ \mu m \end{array}\right\} \quad (9)$$

is the condition.

where: $m$ and $n$ are integers.

Next the cross-port is set to output light of $\lambda$=1.55 µm. From Equation (2) we can then obtain

$$P \approx 1 \ \Leftrightarrow \ 4\eta(1-\eta) \approx 1 \ \Leftrightarrow \ \eta \approx 0.5 \qquad (10)$$

Here, from Equations (4), (5), (9) and (10) we can obtain

$$\kappa \approx \frac{1}{2}\left\{1 \pm \sqrt{1-\frac{C}{\cos^2(\phi_0/2)}}\right\} \quad @\lambda=1.55\ \mu\text{m} \qquad (11)$$

which yields

$$C \approx \frac{1}{2}\left\{1 \pm \sqrt{1-\frac{0.5}{\cos^2(\phi_1/2)}}\right\} \quad @\lambda=1.55\ \mu\text{m} \qquad (12)$$

Summarizing the above, from Equation (9) we can obtain $\phi_1=23\pi$, $21\pi$ (when $\lambda$= 1.31 µm and 1.49 µm respectively). Then letting the waveguide length for phase shifter $T_{\phi 1}$ be $\Delta L_1$ and the equivalent refractive index of the core be neff, the amount of phase shift $\phi_1$ may be represented as $(2\pi/\lambda)\ n_{\mathrm{eff}}\Delta L_1$, and from this we can find that $\Delta L_1$= 0.87 µm. Similarly, letting the waveguide length for phase shifter $T_{\phi 0}$ be $\Delta L_0$, the amount of phase shift $\phi_0$ may be represented as $(2\pi/\lambda)\ n_{\mathrm{eff}}\Delta L_1$, and from Equation (8) we can find that $\Delta L_0$ =3.18 µm. From these values for the amount of phase shift and from Equations (11) and (12), we selected directional couplers having $\kappa$=0.008, 0.026 and 0.040 (when $\lambda$=1.31 µm 1.49 µm and 1.55 µm respectively).

Moving on, the wavelength response of the PLC-MZI-type 3-wavelenth wideband WDM filter calculated on the basis of the circuit parameters that have been derived is shown in Figure 7. From this it can be seen that light in the 1.31-µm and 1.49-µm bands is output to the through-port, while that in the 1.55-µm band is output to the cross-port, and wideband operation is achieved in the 1.31-µm band. It can also be seen that a low loss ripple characteristic is obtained in all of the bands.

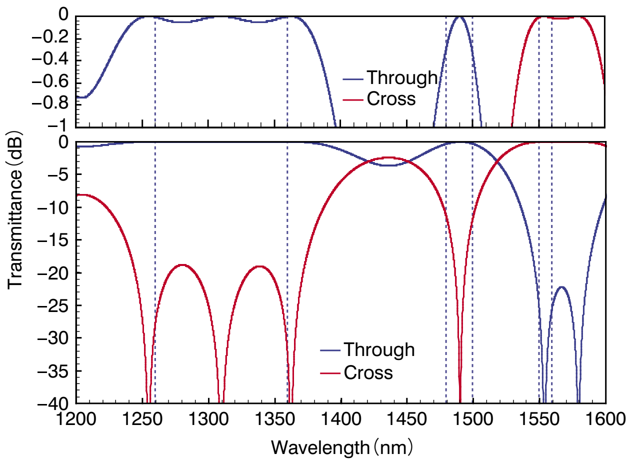



**Figure 7 Calculated wavelength response of PLC-MZI-type 3-wavelenth wideband WDM filter.**

### 2.3 Design for Achieving High-Isolation

From the results described above, it was possible to achieve wideband, low loss ripple operation through the use of the novel optical circuit arrangement proposed in this work. If, however, we examine isolation for each of the bands, we find that it is about 15~20 dB, which is not entirely adequate. We therefore investigated how to use the optical circuit configuration shown in Figure 8 as a means of achieving high isolation [5].

First we adopted a double-pass configuration, in which light would pass through two identical PLC-MZI wideband WDM filters at both the through-port and the cross-port.

Figure 9 shows the calculated wavelength response using this double-pass configuration. From this we can see that isolation of >35 dB was achieved for both the 1.31-µm and 1.55-µm bands, while for the 1.49-µm band, on the other hand, it was only about 22 dB, still inadequate. Accordingly we applied an additional filter consisting of an MZI to the cross-port, thereby improving 1.49-µm band isolation.

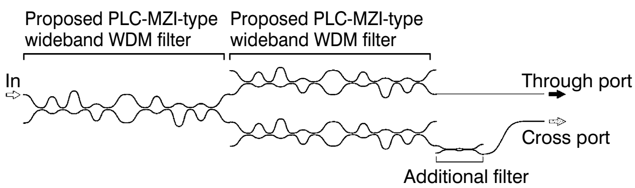



**Figure 8 Schematic configuration for achieving high isolation.**

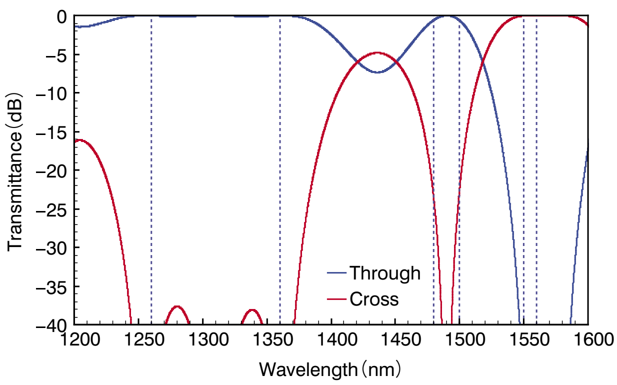



**Figure 9 Calculated wavelength response using double-pass configuration.**

Figure 10 shows the calculated wavelength response using this additional filter. From this we see that by using an additional filter with wavelength characteristics that exhibit a valley in the 1.49-µm band we can enhance 1.49-µm band isolation compared to that with the double-pass configuration alone.

### 2.4 Design for Achieving Reduced Fiber Coupling Loss

To further promote loss lowering, we devised a means of limiting coupling loss to the optical fiber. The PLC-MZI 3-wavelenth wideband WDM filter described above has circuit that is of large scale, and we proceeded with our work on condition that it would be fabricated on a silica-

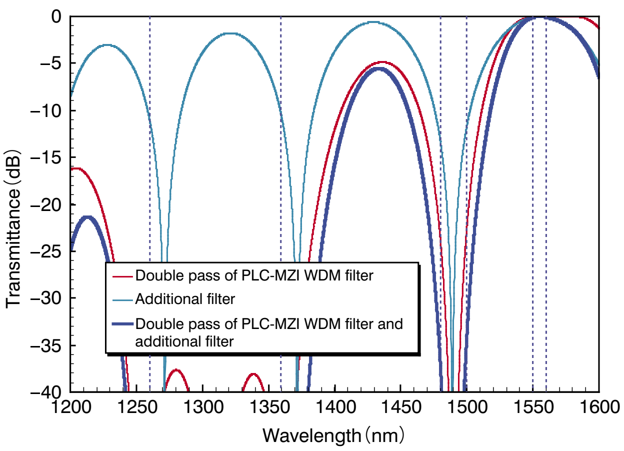



**Figure 10 Calculated wavelength response using additional filter.**

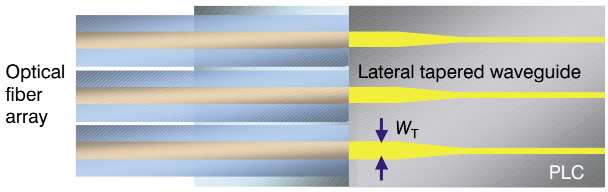



**Figure 11 Schematic configuration of interface between PLC and I/O optical fibers.**

based PLC with a high refractive index difference $\Delta$ of 0.8 %. Thus by using dispersion-shifted fiber (DSF) for the input and output fibers and by introducing lateral tapered waveguides on the input and output ends of the silica-based PLC, we were able to reduce fiber coupling loss.

Figure 12 shows calculated results for the relationship between taper waveguide width $W_T$ and coupling loss. From this we can see that by using DSF and adopting a tapered waveguide with a width of 8.75 µm, we may anticipate a reduction in coupling loss calculated to be approximately 0.4 dB/facet compared to a connection with ordinary single-mode fiber.

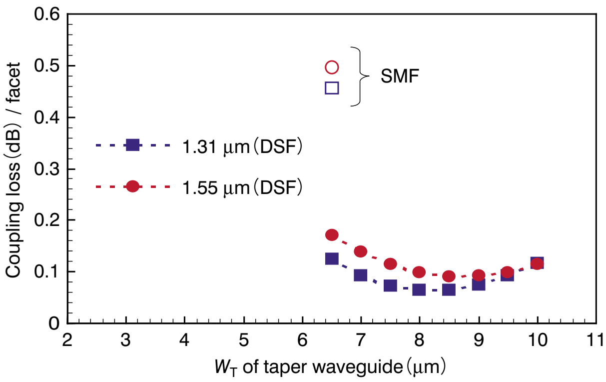



**Figure 12 Relationship between taper waveguide width $W_T$ and coupling loss.**

## 3. RESULT OF FABRICATION

Based on the arguments advanced in Section 2 above, and using the ordinary technology for fabricating silica-based PLC, combining flame hydrolysis deposition, photolithography and reactive ion etching, we fabricated an 8-channel PLC-MZI-type 3-wavelenth wideband WDM filter array on a silicon substrate, which exhibits low loss, low loss ripple and high isolation. Figure 13 shows the waveguide layout.

It may be seen that even including all the reference optical circuits, it has been possible to fabricate onto a chip measuring only 63 × 5.6 mm$^2$. Figure 14 is a photograph showing the fabricated module.

Next we present the results of an evaluation of wavelength response. Measurements were made using an optical spectrum analyzer having a wideband light source. First we compared the calculated values and the measured values to confirm the suitability of the design.

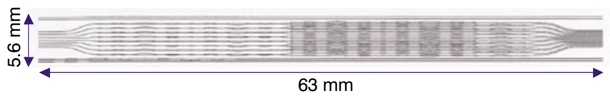



**Figure 13 Waveguide layout for 8-ch PLC-MZI-type 3-wavelenth wideband WDM filter array.**

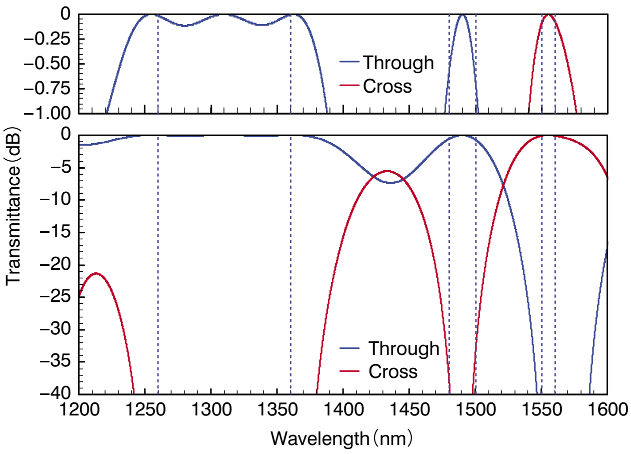

**Figure 14 Fabricated module.**

Figure 15 compares the calculated result (a) and the measured result (b) for the 7th optical circuit of the 8-channel array. It can be seen that there is an extremely high level of agreement between the calculated and measured results, confirming the suitability of this design.

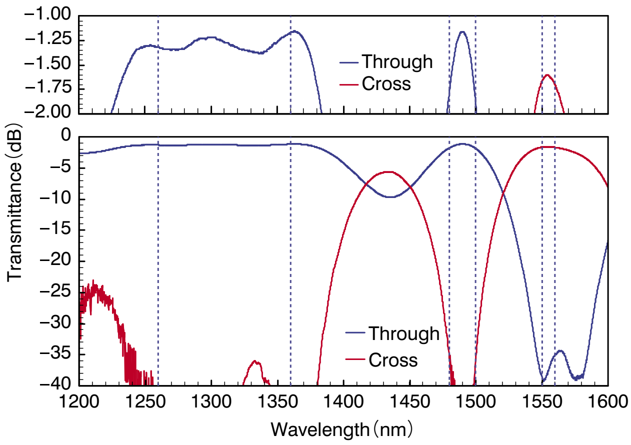
Figure 16 shows the results of an evaluation of wavelength response for all 8 channels of the PLC-MZI-type 3-wavelenth wideband WDM filter array module fabricated in this work, and Table 1 presents a summary of its optical properties. From this it can be seen that good characteristics were obtained for all wavelength bands concerned, namely the 1.31-µm band (1.26~1.36 um), the 1.49-µm band (1.48~1.50 µm) and the 1.55-µm band (1.55~1.56 µm) and for all 8 channels. These characteristics were: insertion loss of <1.96 dB, loss ripple of <0.77 dB, In-to-through-port and In-to-cross-port isolation of >32 dB and through-to-cross-port isolation of >50 dB.

## 4. CONCLUSION

In the run-up to achieving FTTH video distribution services in an economical manner, we have used silica-based PLC technology to develop an 8-ch PLC-MZI 3-wavelenth wideband WDM filter array that utilizes a novel circuit configuration based on the Mach-Zender interferometer. The result was that good characteristics were obtained for all wavelength bands concerned and for all 8 channels, that is to say insertion loss of <1.96 dB, loss ripple of <0.77 dB, and isolation of >32 dB.




**a) Calculated**




**b) Measured**

**Figure 15 Comparison of calculated and measured results for wavelength response of the 7th of 8 channels.**

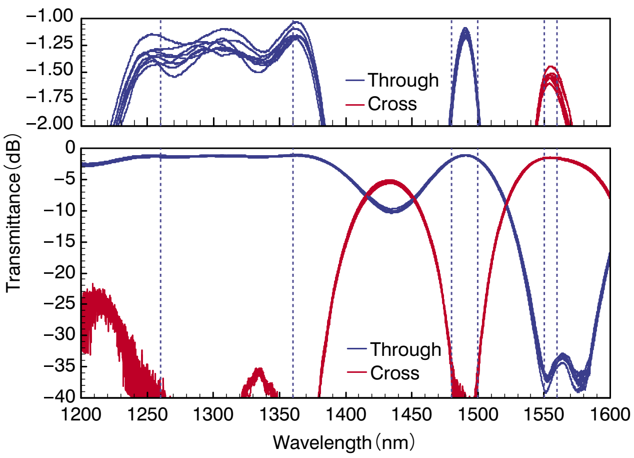



**Figure 16 Measured wavelength response of all 8 channels of the PLC-MZI-type 3-wavelenth wideband WDM filter array module.**

**Table 1 Summary of optical properties of fabricated 8-ch PLC-MZI-type 3-wavelenth wideband WDM filter array module.**

| | Meas. (Worst) | Meas. (Best) | Meas. (Avg) | Design |
|---|---|---|---|---|
| 1.31 μm passband (1.26~1.36 μm) | | | | |
| Ins. loss | 1.54 | 1.32 | 1.42 | — |
| Loss ripple | 0.38 | 0.20 | 0.26 | 0.12 |
| Isolation (In-Cr) | 33.6 | 34.6 | 34.0 | 41.0 |
| Isolation (Th-Cr) | >50.0 | >50.0 | >50.0 | — |
| 1.49 μm passband (1.48~1.50 μm) | | | | |
| Ins. loss | 1.96 | 1.75 | 1.85 | — |
| Loss ripple | 0.77 | 0.65 | 0.71 | 0.67 |
| Isolation (In-Cr) | 32.1 | 34.4 | 33.3 | 34.2 |
| Isolation (Th-Cr) | >50.0 | >50.0 | >50.0 | — |
| 1.55 μm passband (1.55~1.56 μm) | | | | |
| Ins. loss | 1.71 | 1.53 | 1.63 | — |
| Loss ripple | 0.13 | 0.08 | 0.10 | 0.09 |
| Isolation (In-Th) | 32.0 | 33.1 | 32.2 | 45.0 |
| Isolation (Th-Cr) | >50.0 | >50.0 | >50.0 | — |

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