Passive Optical Components and Their Applications to FTTH Networks

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This paper describes technologies related to passive optical components such as fused fiber couplers, optical filters, splitters and fiber gratings. These components have been actively deployed in FTTH (Fiber to the Home) networks. A splitter connects transmission equipment at a central office to a plurality of users, leading to economical PDS (Passive Double Star) networks. A splitter with a directional coupler circuit or an optical filter enables multiplexing of video signals. A fiber grating external cavity laser diode is suitable as an OTDR (Optical Time Domain Reflectometer) light source. The light from OTDR is coupled to the main route through such a highly integrated device as a PLC coupler or a tape fiber fused coupler to be reflected at a terminal filter that employs an optical connector embedded with a chirped fiber grating.

Keywords: FTTH, fused fiber coupler, splitter, fiber grating, PLC

1. Introduction

Optical fiber communication has brought us a new Internet society. In Japan, FTTH (Fiber to the Home) networks, in which optical fibers are installed directly to users' homes, have been so popular that the number of contractors for FTTH service has exceeded fifteen millions as of May 2010. "Optical fiber," "light source," and "photo detector" are said to be three key elements of optical fiber communication. It should be noted, however, that various kinds of optical components and related technologies, besides those three elements, have contributed to the evolution of optical communication, improving functionalities, reliability, and economical efficiency of optical networks. This report focuses on "passive components" without functions of optical/electrical conversion, and describes key technological points including development in Sumitomo Electric Industries, Ltd., and their deployment in FTTH networks.

2. Principle, Design, and Manufacturing Process for Passive Components

2-1 Fiber fused coupler

A fiber fused coupler is one of the most popular passive components for wavelength multi/demultiplexing or branching/combining of optical signals. It is manufactured by a simple method that fuses two optical fibers and elongates along their longitudinal axis as shown in **Fig. 1**[1].

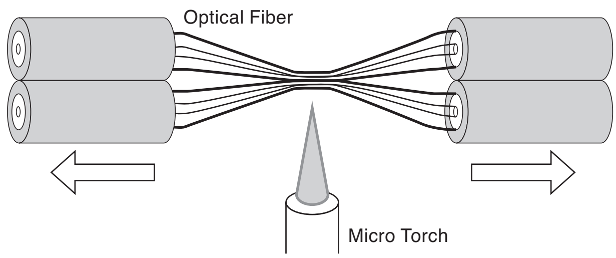


Fig. 1. Fiber Fused Coupler

When the fibers are elongated, optical confinement in the core becomes weaker and the field broadens to the entire cladding region leading to coupling to another fiber. If the structures of the fibers are identical, that is, propagation constants are the same as each other, 100% of optical power couples to another fiber with a specific propagation length and it returns back to the original fiber with further propagation length. Since this propagation length is dependent on wavelength, a specific wavelength can be led to one output fiber and another specific wavelength can be led to another output fiber under an appropriate propagation length, realizing wavelength multi/demultiplexing function, as shown in **Fig. 2 (a)**. When the structures of fibers are not identical, wavelength dependence is reduced although the coupling cannot reach 100%. Utilizing such property, a wavelength independent coupler can be manufactured as shown in **Fig. 2 (b)**.

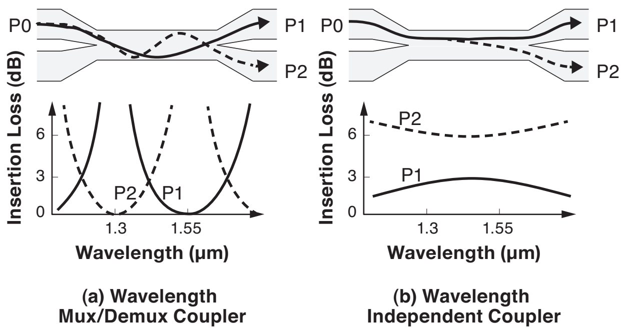


Fig. 2. Function of Fiber Fused Coupler

Sumitomo Electric has developed fiber fused couplers using arrayed fiber ribbons(2) as shown in **Fig. 3** for applications where a plurality of couplers are employed. This technology features simultaneous manufacturing of a plurality of couplers as well as realizing smaller footprint and easy handling for fiber routing owing to the ribbonized fibers as pigtails.

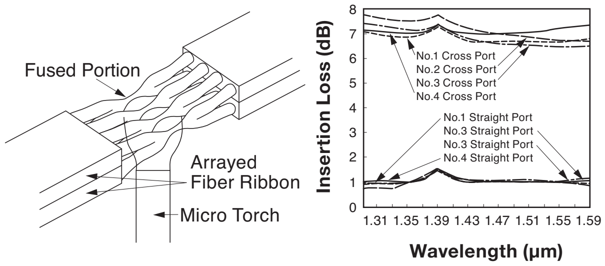


Fig. 3. Fiber Fused Coupler Using Arrayed Fiber Ribbons

2-2 Optical filter

An optical filter is a wavelength multi/demultiplexing device with a dielectric multi-layered thin film, which can add or drop a specific wavelength in the midst of a fiber. A dielectric multilayered film consists of many layers with different refractive index deposited on a transparent substrate, reflecting or transmitting a specific wavelength owing to interference of the light reflected at the layer interfaces. **Figure 4** is a typical structure of an optical filter. A thin film filter is inserted in the collimated optics by gradient index lenses at the end faces of a twin fiber ferule and a single fiber ferule.

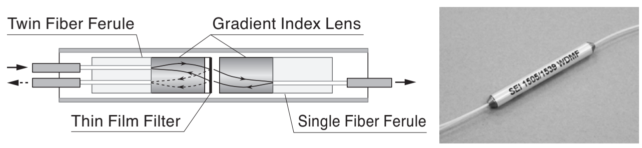


Fig. 4. Structure of Filter Module

In a fiber embedded filter(1), a thin film filter is inserted and glued in a clearance made by dicing an optical fiber fixed on a base. In order to reduce loss due to the gap between optical fibers, the thickness of the substrate should be less than several 10 μm. **Figure 5** is an example of a fiber embedded filter using a single optical fiber fixed in a V-groove of a base material. Replacing the fiber to a fiber ribbon, a plurality of filters can be made using one thin film filter. By dicing a ferule of an optical connector and inserting a thin film filter, a connector with filter function can be realized.

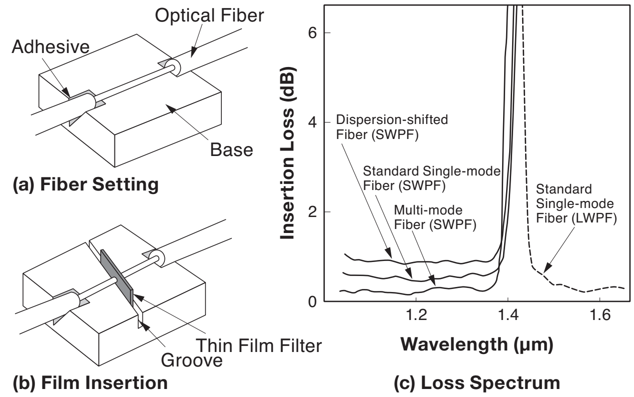


Fig. 5. Fiber Embedded Filter

2-3 Optical splitter

An optical splitter is a device dividing optical power from an optical fiber into a plurality of optical fibers. A PLC*1 is generally used especially for branch degrees more than eight, while fiber fused couplers are applicable for branch degrees up to four. **Figure 6** shows a typical structure of an optical splitter(3). Fiber arrays, in which input/output fibers are arranged, are aligned to an optical circuit of a PLC chip and fixed with UV curable adhesive. In order to eliminate back reflection from the interface with the adhesive layer, the fiber arrays and PLC chip have oblique end faces. Since an attenuation in an optical circuit of a PLC is less than 0.1dB/cm, total excess attenuation including coupling loss at the interface between fiber arrays and a PLC chip is as low as 1dB or less. Typically, a uniformity of branching loss is less than 1dB and a return loss is less than -50dB. It should be noted that the cores of the fibers and a PLC chip should be positioned with an accuracy of submicron order to realize such low insertion loss as above mentioned. The accuracy of the fiber array depends on geometry of optical fibers and especially on the accuracy of processing of V-groove.

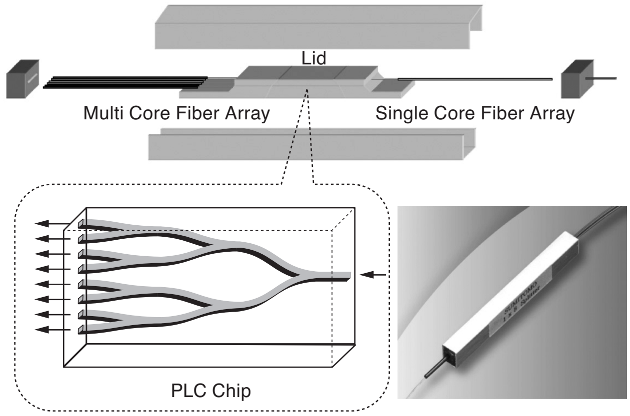


Fig. 6. Structure of Splitter

2-4 Fiber grating

(1) Principle of fiber gratings

Fiber gratings are periodical perturbation of refractive index of optical fibers manufactured by refractive index increase of silica glass due to UV irradiation, being categorized into a short period gratings (**Fig. 7 (a)**) and a long period gratings (**Fig. 7 (b)**)[(4),(5)]. A short period grating, whose refractive index period is in an order of the wavelength, selectively reflects a specific wavelength (Bragg wavelength) λ_B by Bragg diffraction. Bragg wavelength λ_B can be expressed as **Equation (1)**, using an effective refractive index n of a propagation mode and an index period Λ,

$$\lambda_B = 2n\Lambda \quad \cdots\cdots (1)$$

and a reflectivity R_B can be expressed as **Equation (2)**, using a length of grating L and a refractive index increment Δn,

$$R_B = \tanh^2 (\pi L \cdot \Delta n \cdot \eta / \lambda_B) \quad \cdots\cdots (2)$$

where η is a power fraction of propagation light confined in a core. In case of a typical short period grating for 1550nm use, Λ is around 0.5μm, the total number of refractive index layers therefore becomes as large as twenty thousands for a grating with a length L of 10mm. Thanks to such large number of layers, a sharp spectrum characteristics as shown in **Fig. 8**, which is never realized by other kinds of optical filters, can be obtained even though the UV induced index increment is only 10^{-3} at most.

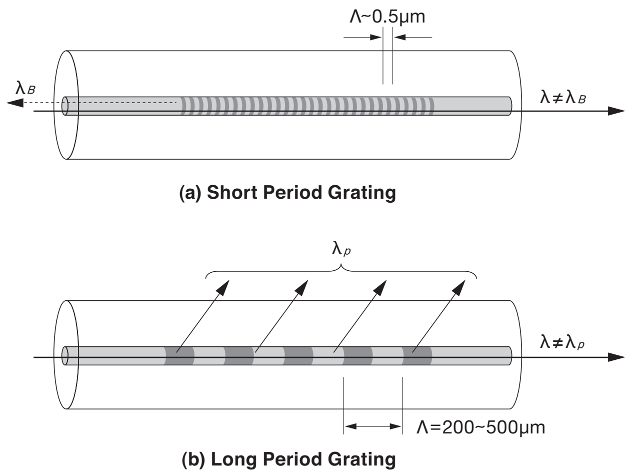


Fig. 7. Structure of Fiber Grating

For a long period grating with an index period Λ as long as several hundred μm, some portion of light propagating in the core couples with cladding modes and attenuates. With a propagation coefficient for a fundamental mode β_{core} and that for a cladding mode β_{clad}, a coupling coefficient ε between a fundamental mode in a core and a cladding mode is expressed as **Equation (3)**,

$$\varepsilon = \frac{\sin^2\{kL\sqrt{1+(\delta/k)^2}\}}{1+(\delta/k)^2} \quad \cdots\cdots (3)$$

$$\delta = (1/2) \quad (\beta_{core} - \beta_{clad} - 2\pi / \Lambda) \quad \cdots\cdots (4)$$

where k is a coupling constant. At the wavelength λ_p for the attenuation peak of a long period grating, ε becomes maximum with $\delta = 0$. λ_p can be expressed as **Equation (5)** by using an effective refractive index for a core propagation mode $n_{core} = \beta_{core}/(2\pi / \lambda_p)$ and that for a cladding mode $n_{clad} = \beta_{clad}/(2\pi / \lambda_p)$.

$$\lambda_p = \Lambda \ (n_{core} - n_{clad}) \quad \cdots\cdots (5)$$

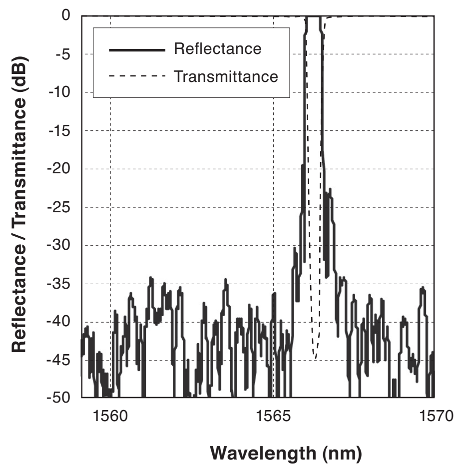


Fig. 8. Example of Transmission/Reflection Spectrum for Short Period Grating

(2) Manufacturing method of fiber gratings

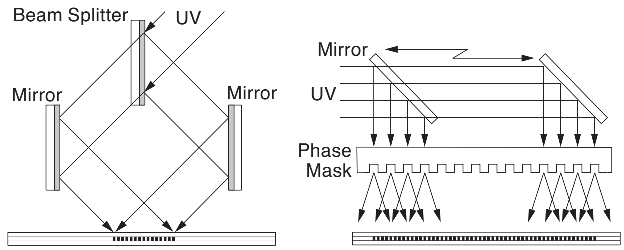
When UV light with a wavelength of around 240 nm is irradiated to germania (GeO_2)-added silica (SiO_2) glass, the Ge-Si bond, an oxygen deficient center, absorbs UV light and some new defects are generated. This reaction causes a change of absorption spectrum, leading to the increase of a refractive index. Density change accompanying with the defect formation is considered to be another factor for a refractive index increase. In manufacturing of fiber gratings, KrF excimer laser (248nm) or SHG of Ar ion laser (244nm) is often used. An effective method for obtaining much more index increment is "hydrogen loading," where optical fiber is immersed in a hydrogen environment so as to absorb hydrogen up to several mol% in advance of UV irradiation. For example, if an optical fiber is immersed in a hydrogen atmosphere with a pressure more than 100-200 atm for one to two weeks at room temperature, a refractive index increment of $1\text{-}5\times10^{-3}$ can be obtained by UV irradiation.

A short period grating, whose period of index change is in an order of wavelength of light, can be manufactured by illuminating the interference pattern of UV light from the lateral side of the optical fiber. **Figure 9** shows typical two methods: two beam interference method and phase mask method.

In the two beam interference method, since a grating period Λ and an interference angle θ have a relationship of **Equation (6)**, an arbitrary period Λ can be obtained by controlling the interference angle θ.

$$\Lambda = \lambda_{UV} / 2 \cdot \sin\theta \quad \cdots\cdots (6)$$

The phase mask method utilizes the interference pattern between diffracted beams of +1 and -1 orders from a phase mask, which is a transmission type grating made of silica with a surface in a square wave shape, where 0-th order beam is suppressed by a phase shift of π between the beams from the concave and the convex portions. Since the period of the interference pattern is just a half of that of the phase mask, good reproducibility can be expected by using a highly precise phase mask.



(a) Two Beam Interference Method **(b) Phase Mask Method**

Fig. 9. Manufacturing Methods for Short Period Gratings

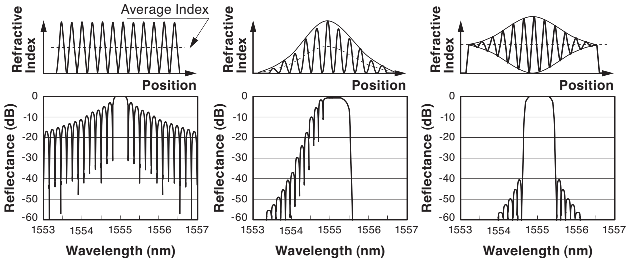
A long period grating with a longer index period Λ can be manufactured by irradiating UV light to the selected portion with a slit or a line-and-space mask, just the same as a cyanotype.

A UV induced refractive index increment gradually relaxes with time, and the time and temperature dependence of the amount of relaxation has been quantitatively formalized[6]. By thermal aging of a fiber grating just after the UV irradiation, it is possible to accelerate the relaxation, resulting in sufficient stability for long term use.

(3) Design of short period grating

In a spectrum response of a short period grating with a uniform structure along the fiber, sub-peaks appear at the both sides of Bragg wavelength, as shown on **Fig. 10 (a)**, which obstructs the realization of a sharp spectrum.

The sub-peaks can be suppressed by making the envelope of the grating into a Gaussian shape, as shown in **Fig. 10 (b)-(c)**. This method is called "apodization". In the case of **Fig. 10 (b)**, where the average index is also in a Gaussian shape, the sub-peaks at the longer wavelength side disappear, however a series of peaks at the shorter wavelength region than Bragg wavelength appear. These peaks are attributed to Fabry-Perot resonation, that is, multiple reflection between two portions with the same average index. As shown in **Fig. 10 (c)**, equalization of the average refractive index along the whole grating region can suppress Fabry-Perot resonation, leading to a sharp reflection spectrum.



(a) Without Apotize **(b) With Apotize** **(c) With Apotize and Uniform Average Index**

Fig. 10. Improvement for Reflection Spectrum of Short Period Grating

In the mechanism of the UV induced refractive index increment, GeO_2 is an indispensable factor. Therefore, for standard optical fibers, a grating is formed in the core where GeO_2 is added. On the other hand, the electromagnetic field of the propagation mode, a single-mode fiber distributes not only in the core but in the cladding. Hence some portion of the propagation mode is diffracted at the core/cladding boundary and couples with backward cladding modes, resulting in radiation loss at the shorter side of Bragg wavelength as shown in **Fig. 11**. In order to suppress this radiation loss, diffraction at the core/cladding boundary has to be reduced. For this purpose, a special fiber with a cladding added with GeO_2 has been developed. Using this fiber, gratings can be formed in the cladding as well as in the core so that radiation loss can be sufficiently reduced. In this fiber, fluorine (F), which decreases the refractive index of SiO_2, is added to the

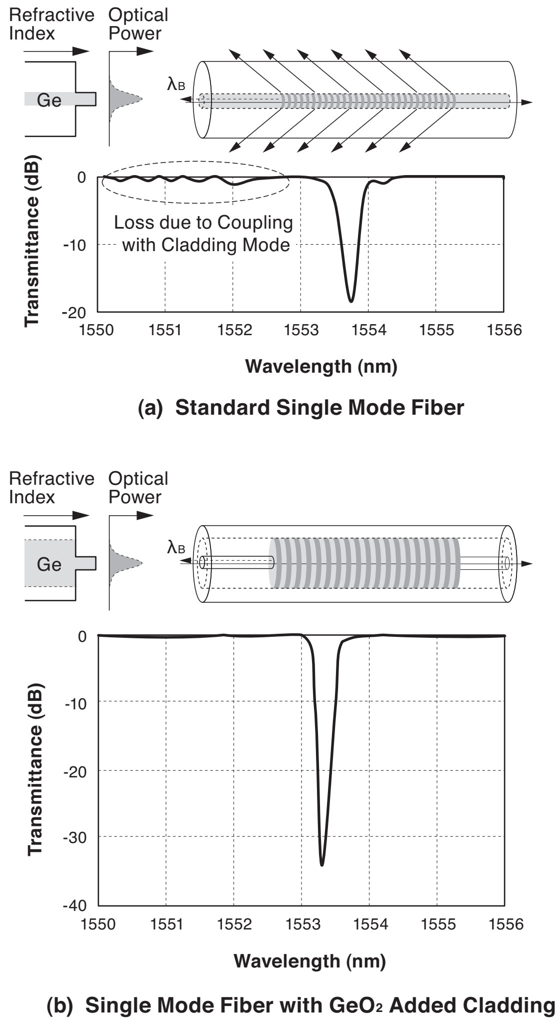


Fig. 11. Reduction in Cladding Mode Coupling Loss

cladding to compensate the refractive index increase due to GeO_2 content.

Bragg wavelength of short period gratings depends on temperature. From **Equation (1)**, temperature dependence of Bragg wavelength λ_B can be derived as **Equation (7)**,

$$\partial \lambda_B / \partial T = \lambda_B \{ \alpha + (\partial n / \partial T) / n \} \quad \cdots\cdots\cdots\cdots (7)$$

where the first term α is a CTE (coefficient of thermal expansion) of silica glass (5.5×10^{-7}/deg). The second term ∂n/∂T is a temperature dependence of the refractive index of silica (7.5×10^{-6}/deg), and it is a dominant factor of the temperature dependence of Bragg wavelength. It is possible to athermalize short period gratings by some artifices in packaging that applies higher tension to the grating at lower temperature. For example, as shown in **Fig. 12 (a)**, one method is fixing a fiber grating on a base with a negative CTE such as a tube made of oriented liquid crystal polymer and a special polycrystalline glass plate. Another approach is a composite structure where the both ends of a fiber grating are fixed on parts with a high CTE, and the parts are fixed on the end of a base with a low CTE, as shown in **Fig. 12 (b)**.

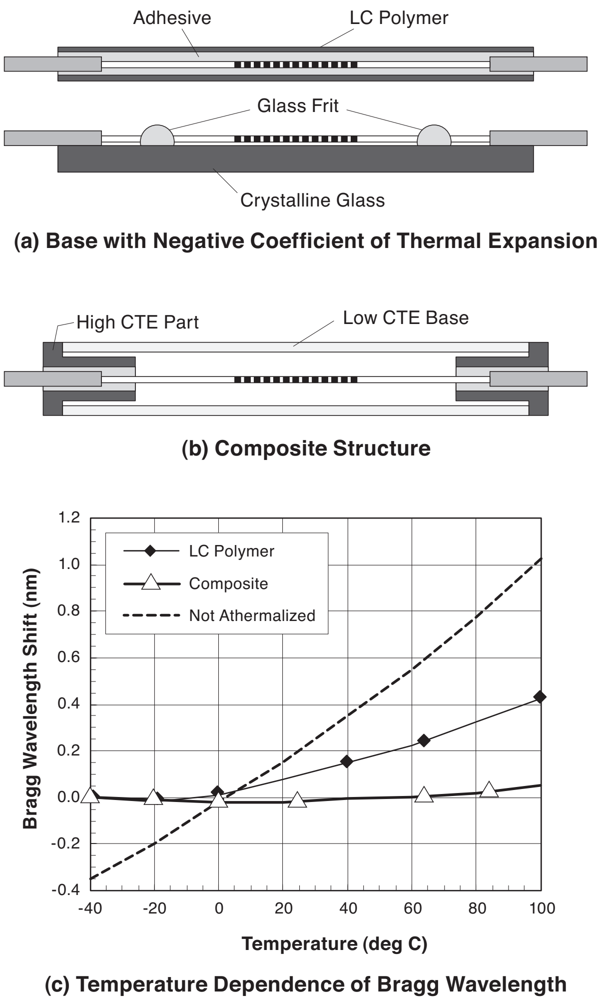


Fig. 12. Athermalizing for Short Period Grating

3. Passive Components in FTTH networks

In FTTH networks, PON (Passive Optical Network) systems based on an architecture called PDS (Passive Double Star) have been employed, where an OLT (Optical Line Terminal), transmission equipment in the central office, is connected to a plurality of ONUs (Optical Network Units), transmission equipment at users, via an optical splitter in the midst of the optical transmission line. This system allows many users to share the cost of equipment in the central office and optical fiber cable, reducing the cost burden of individual users. In this section, various roles of passive optical components in FTTH networks are described.

3-1 Branching of optical signals

Figure 13 schematically shows a typical FTTH network in Japan. 1 × 4 splitters in a central office and 1 × 8 splitters in an aerial closure near users are installed.

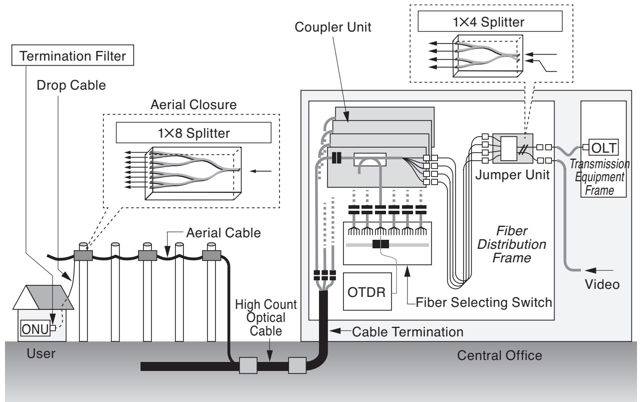


Fig. 13. FTTH Optical Network

ITU-T[(6)] and IEEE[(7)] have standardized system structures for G-PON (Gigabit-capable Passive Optical Network) and GE-PON (Gigabit Ethernet Passive Optical Network), respectively. The maximum number of branches is 64 for G-PON and 32 for GE-PON, and signal wavelengths are allocated as 1490 nm band for downstream signals, 1310 nm band for upstream signals, and 1550 nm band for video. In addition, 1650 nm band is used for network surveillance. Therefore optical characteristics applicable to a wide wavelength range from 1300 to 1650 nm are required for optical splitters. In the case of 64 branches, intrinsic branching loss reaches 18 dB. The number of branches is decided considering transmission distance, status of transmission lines, loss budget and so on.

3-2 Multi/demultiplexing of video signals

As described above, 1310 nm band and 1490 nm band are used for upstream and downstream signals, respectively, for PON systems. In order to multi/demultiplex these wavelengths, dielectric multilayered thin films are often used in an OLT and an ONU. For multiplexing of video signals of 1550 nm band, which locates between OLT and users' premises, distinctive technologies are employed according to the position.

When video signals are multiplexed at the vicinity of optical splitters, the first stage of Y-branch in a PLC type splitter is replaced to a 2 × 2 directional coupler, as shown in **Fig. 14**. By launching 1490 nm downstream signals and 1550 nm video signals at each input port, the function of multiplexing downstream and video signals and that of branching can be obtained at the same time, where the upstream signals going through the video input port are eliminated by an additional optical filter.

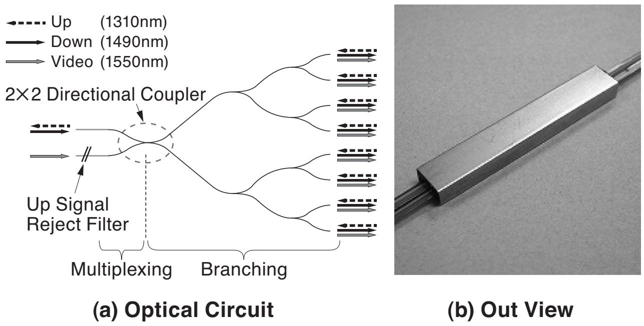


Fig. 14. Multiplexing-Branching Splitter

When video signals are multiplexed in the midst of the network, optical filters shown in **Fig. 4** are often used. Though an optical filter is usually a single-fiber device, highly integrated filter devices have also been developed(8). The structure is shown in **Fig. 15**, where a dielectric multi-layered film is sandwiched between PLC chips, PLC-1 and PLC-2. PLC-1 has an optical branching circuit with a common port and a reflection port, and PLC-2 has a transmission port. Upstream signals (1310 nm) enter from the common port, and go out from the transmission port through the thin film, while downstream signals (1490 nm) go in reverse. Video signals (1550 nm) come from the reflection port and go to the common port. **Figure 16** is an example of insertion loss and isolation spectra. It has been reported(8) that up to six count optical filters have been successfully integrated on a pair of PLC-chips.

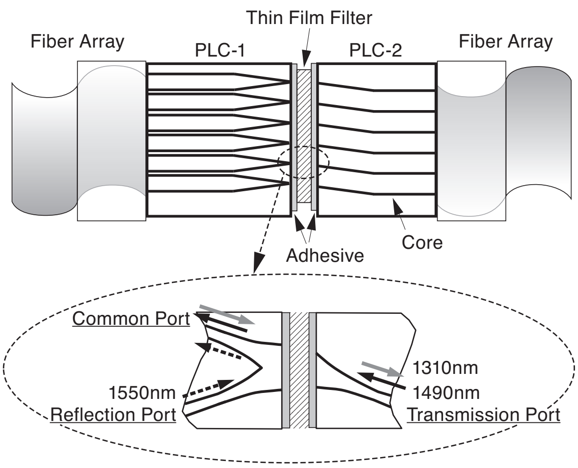


Fig. 15. Integrated PLC Type Optical Filter

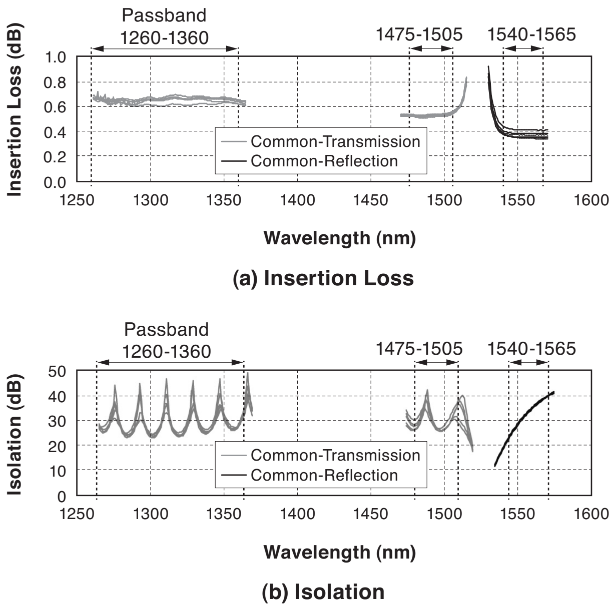


Fig. 16. Example of Performance for Integrated PLC Type Optical Filter

3-3 Passive components for optical surveillance systems

As shown in **Fig. 13**, for maintenance and surveillance of FTTH networks, a monitoring light with a wavelength of 1650nm from an OTDR*2, a measurement instrument located in a central office, is coupled to the main network line through a fiber selecting switch, and a coupler unit in which PLC type couplers or fiber fused couplers are stored. Since equipments in a central office should accommodate huge amount of optical fiber in a limited space, highly integrated devices, such as PLC type couplers or fiber fused couplers using arrayed fiber ribbon, are often employed.

In a light source in an OTDR, a fiber grating is utilized. A fiber grating can be used as an external oscillator mirror for a laser diode to stabilize the oscillation wavelength, and to narrow a spectral line width. **Figure 17** shows the basic structure(8) of a fiber grating external cavity laser diode. An oscillator is made by the rear end face of an SOA (Semiconductor Optical Amplifier) and the short period fiber grating, and an oscillating wavelength is locked by Bragg wavelength of the grating. For an OTDR, a wider line width of the oscillating wavelength is advantageous to suppress interference noise. For this purpose, several methods can be applied such as shortening the length of the grating and chirped fiber grating. In a chirped fiber grating, the grating period gradually changes along the fiber axis. **Figure 18** is an example of output spectrum of an external cavity laser diode with a chirped fiber grating, where the 20 dB down line width is broadened to 7 nm.

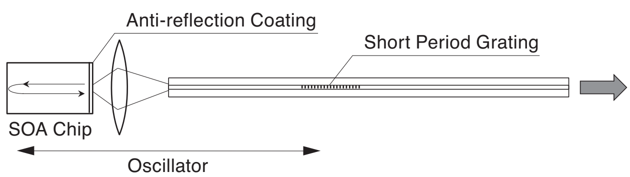


Fig. 17. Fiber Grating External Cavity Laser Diode

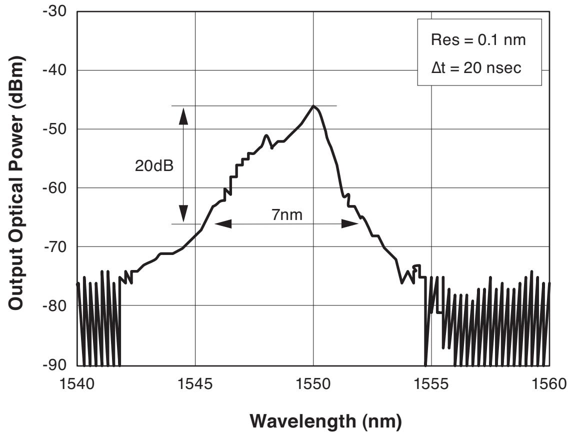


Fig. 18. Output Spectrum for Fiber Grating External Cavity Laser

In order to confirm whether the monitoring light reaches the user, an optical filter to reflect the monitoring light is installed at the terminal point of the user. The termination filter has a function to prevent the monitoring light from entering the ONU of the user. At the initial stage of the development, the termination filter was a thin film filter embedded in the ferule of an SC connector to be connected to an ONU. However, as deployment of FTTH service has been proceeded, fiber-grating-embedded connectors have become popular. The structure and an example of reflection/transmission spectra are shown in **Fig. 19** and **Fig. 20**, respectively. Considering the wavelength variation of the monitoring light, a chirped grating with a broadened bandwidth for transmission and reflection spectra is employed. A fiber grating is inserted in a ferule of a connector and fixed with adhesive. It is easy to obtain reflectivity higher than 90%, and advantageous from the view point of productivity and cost. Currently, a field installable connector embedded with a fiber grating has been popular for a termination filter.

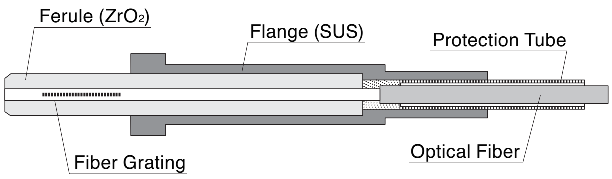


Fig. 19. Fiber Grating Embedded Optical Connector

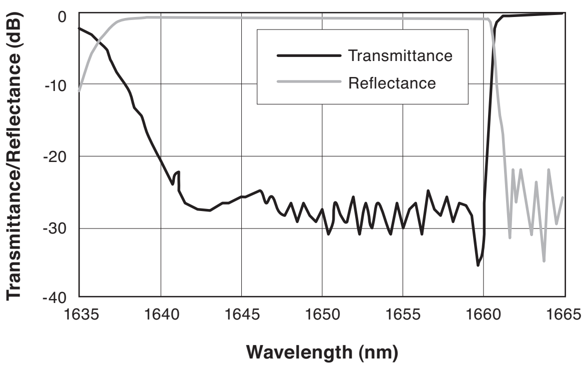


Fig. 20. Transmission/Reflection Spectra for 1650 nm Band Reject Fiber Grating Embedded Optical Connector

4. Conclusion

As for passive optical components, technological key points and their roles in FTTH networks are described. Passive components are being employed not only in FTTH networks but in metro/core networks. Metro/core networks evolutionally progressed owing to optical fiber amplifiers and DWDM (Dense Wavelength Division Multiplexing) systems from late 1980's to 1990's, and passive optical components played important roles for such break through. We are going to continue the development of passive components, struggling with cost reduction and reliability issues.

Technical Term

*1 PLC (Planar Lightwave Circuit)
PLC is a device with optical circuits built in a silica based transparent film on a substrate made of silica glass or silicon by using a semiconductor process such as photolithography and dry etching.

*2 OTDR (Optical Time Domain Reflectometer)
An OTDR is an instrument to measure an attenuation distribution in a fiber by injecting an optical pulse and analyzing a time and a power of returned light reflected from each point of the optical fibers.

References

(1) M. Fukuma, T. Shitomi, H. Suganuma, T. Hattori, M. Shigematsu, and H. Takimoto, "Development of Optical Fiber Type Passive Components," SEI Technical Review (in Japanese), Vol.136, pp.60-67, Mar. 1990.

(2) Y. Ishiguro, E. Sasaoka, Y. Kobayashi, T. Moriya, S. Semura, H. Yokota, T. Wakinosono, Y. Yamada, and Y. Sakata, "Fiber Fused Coupler Using Arrayed Fiber Ribbons," SEI Technical Review (in Japanese), Vol.145, pp.16-19, Sep. 1994.

(3) H. Kanamori, "Passive Optical Components for FTTH Network," OPTRONICS (in Japanese), No.297, pp.135-139, Sep. 2006.

(4) H. Kanamori, "Finer Gratings," The Journal of IEICE (in Japanese), Vol.82, No.7, pp.731-739, Jul. 1999.

(5) A. Inoue, T. Iwashima, K. Sakai, T. Ito, M. Kakui, T. Enomoto, and H. Kanamori, "Development of Fiber Gratings for WDM Transmission," SEI Technical Review (in Japanese), Vol.152, pp.30-35, Mar. 1998.

(6) ITU-T G.984.1/ITU-T G.984-2

(7) IEEE Std802.3ah-2004

(8) M. Harumoto, O. Shimakawa, K. Takahashi, T. Sano, and M. Katayama, "Development of Multi-Channel Three Wavelengths Multiplexing Filter for FTTH application," SEI Technical Review (in Japanese) No.170, pp.6-10, Jan. 2007.

(9) M. Shigehara, A. Inoue, and H. Maki, "Wavelength Stabilized and Narrow Bandwidth Light Source for OTDR," OECC'97 Tech Dig., 9D1-3, pp.210-211, Jul. 1997.
(10) I. Matsuura, K. Sakai, A. Inoue, H. Kanamori, and H. Maki, "SC Connectors with 1.65μm Wavelength Cut Filter of Fiber Grating," Proceedings of the 1998 IEICE General Conference (in Japanese), B-10-23, Sep. 1998.

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