PLC Products for FTTH Systems

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ABSTRACT Two types of planar lightwave circuit (PLC) products--chips and modules--have been developed to serve the rapidly expanding area of fiber-to-the-home (FTTH) systems. PLC technology, which has for some time past been incorporated in products for WDM systems, has here been extended to FTTH applications, making possible the development of PLC products that combine low cost and high performance. Reliability tests have also been carried out, confirming that they also offer high long-term reliability. This paper reports on PLC products that are representative of those for FTTH applications--a wavelength-insensitive coupler (WINC), and 1 x 4, 1 x 8 and 1 x 16 splitters.

1. INTRODUCTION

Recently Japan has seen rapid diffusion of broadband services, of which the asymmetric digital subscriber line (ADSL) is currently the most widely used. But the number of subscribers to FTTH systems, growing more than twice as fast as ADSL [1], has already reached the 1 million mark and is expected to increase at rates even faster than before.

Among broadband services FTTH systems are the fastest and most stable, but growth has been impeded by higher initial cost and usage tariffs. At the present time initial costs are dropping and usage tariffs have also come close to those for ADSLs, so that rapid diffusion has begun. To reduce tariffs, telecom carriers are proceeding with the introduction of passive optical network (PON) systems, shown in Figure 1, in which a number of subscribers can use a single fiber, and these systems involve the use of large numbers of components that split the optical signal (optical splitters).

In NTT's B-Flets system, for example, there are 8-arrayed 1 x 4 splitters and 4-arrayed of 1 x 8 splitters used inside the exchange office, and 1 x 4 and 1 x 8 splitters outside the office. This system is also a world leader in having an optical monitoring system that uses a WINC to insert a monitoring signal into the system [2), 3)].

And in any future transition from the 100-Mbps PON systems that are today's standard to a giga-PON or giga Ethernet-PON (G-PON or GE-PON), picture image delivery will also be possible over optical fibers, and this will require components with WDM functions, to split the IP signal and picture image signal.

Broadband services are also undergoing similar expansion outside Japan, and field tests have started for the introduction of FTTH systems. Since it is to be expected that within a few years diffusion of FTTH systems will also get under way overseas, we can anticipate significant growth in optical components that are FTTH-related.

FTTH components will differ, however, from the components that have in the past been the mainstay of trunk line systems in that since so many are used they must have very low unit costs.

That is why we have developed chips using PLC technology, which are suited to the fabrication of FTTH system components. Since PLC technology, like semiconductor processes, permits the batched fabrication of circuits on silicon or silica substrates, it is possible for a large number of chips at one time to be supplied cheaply. The fabrication process involves forming the glass film by flame hydrolysis deposition (FHD), core channelization using a resist and optical mask, patterning, and dry etching by RIE. In addition we have developed a highly reliable low-cost module suited to this chip.

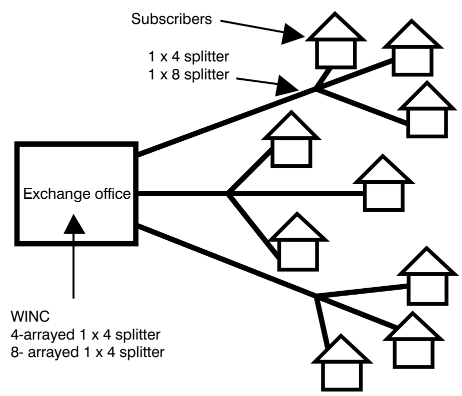

Figure 1 Passive optical network (PON) system.

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This paper reports on a wavelength-insensitive coupler (WINC) [3], 8-arrayed 1 x 4 splitters--components for use in NTT's B-Flets, and 1 x 4, 1 x 8 and 1 x 16 splitters. We are also scheduled to proceed with the development of other products for FTTH systems using PLC technology, such as a 1 x 32 splitter and WDM coupler.

2. PLC CHIP FOR FTTH SYSTEMS

Here we describe a wavelength-insensitive coupler (WINC) and splitters developed as PLC chips for FTTH systems.

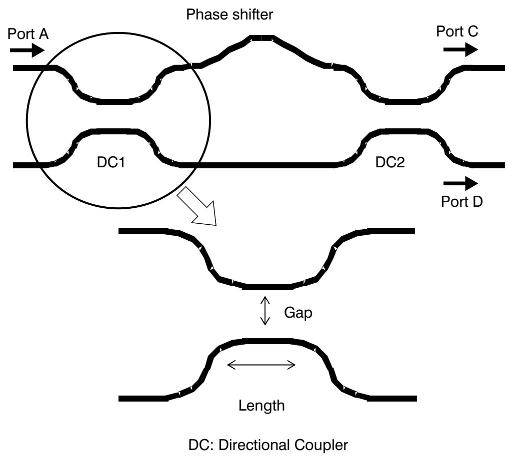

Figure 2 WINC circuit configuration.

2.1 WINC

The WINC is a coupler that has virtually the same branching ratio in both the 1.3- and 1.55-μm bands, and is a component of line monitoring systems used in the NTT exchange offices. Figure 2 shows the circuit configuration, which consists of a Mach-Zehnder interferometer incorporating two directional couplers (DCs) and a phase shifter. By checking the difference between the gaps and lengths of the two DCs and the length of the waveguide of the phase shifter, it is possible to cancel out the wavelength dependence of one of the DCs and obtain virtually the same coupling efficiency over a broad bandwidth.

Referring to Figure 2, coupling efficiency R may be defined by

$$R=\frac{P_D}{P_C+P_C} \quad (1)$$

where:
P_C is the power of the signal input from Port A and output from Port C, and
P_D is the power of the signal output from Port D.

2.1.1 WINC Design

FTTH system components must be low in cost, and yields must be high. Thus a design was adopted in which coupling efficiency remains stable despite process variations.

Here coupling efficiency may be represented by [3]

$$R=\cos^2(\phi)\sin^2(\theta_1+\theta_2)+\sin^2(\phi)\sin^2(\theta_1-\theta_2) \quad (2)$$

where:
2ϕ is the phase difference generated by the phase shifter,
θ_1 is the phase representation of the coupling efficiency of DC1; and similarly
θ_2 is the phase representation of the coupling efficiency of DC2.

The first term of this Equation can, in the design, be made extremely small relative to the second term by suitable selection of the phase shifter phase. In this case it is sufficient in considering variation in coupling efficiency R, to look at the second term only. ϕ is a value that is determined by the length of the phase shifter and since this is determined by the precision of the mask used in patterning, may be considered as not varying. θ is a function of the gap and length of the DC, but since the length is determined by the precision of the mask it does not vary. It can thus be seen that the thing to be taken into account at the design stage is deviations in DC gap.

The gap will change due to deviations in etching and the conditions of burying of the upper clad, but through our experience with the process we have found the following. Where G_1 and G_2 represent the gaps of the two DCs and ΔG_1 and ΔG_2 the variations in them, we observe that when G_1 and G_2 are not equal ΔG_1 and ΔG_2 are generally not equal, and when G_1 and G_2 are equal ΔG_1 and ΔG_2 are generally equal.

Thus when the gaps of the two DCs are equal the amount of variation is substantially the same, so we may consider that the change in (θ_1-θ_2), the second term of Equation (2) becomes less.

Calculations were carried out to confirm this. Assuming that $\Delta G_1=\Delta G_2$ for both cases-- G_1 equal to G_2 and G_1 not equal to G_2. Figure 3 plots ΔG_1 ($=\Delta G_2$) on the horizontal axis against the amount of variation in coupling ratio with respect to the target coupling efficiency of 21 % on the vertical axis. It can be seen that the variation was smaller when G_1 and G_2 were equal than when they were not.

In Figure 4, considering the variation that could occur when G_1 is not equal to G_2, we plot the case in which G_1 is 0 and only G_2 varies, in an analogous manner to Figure 3, with G_2 on the horizontal axis and the variation in coupling efficiency on the vertical axis. Both show the opposite movement, and this too points up the fact that stable characteristics are difficult to achieve in a design in which G_1 and G_2 are not equal.

2.1.2 WINC Fabrication

Based on these design-stage considerations, we designed and fabricated a WINC in which coupling efficiency would be constant over a broad bandwidth under the condition that G_1 and G_2 are equal. For purposes of comparison we also fabricated a WINC designed with G_1 and G_2 not equal. Figures 5 and 6 show the results, and it can be seen that in both the 1.31- and 1.55-μm bands the WINCs fabricated with G_1 and G_2 equal had a far lower incidence of deviation in coupling efficiency.

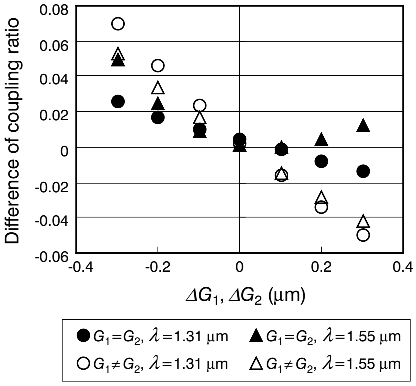

Figure 3 Variation in coupling ratio between WINCs with same and different DC gap.

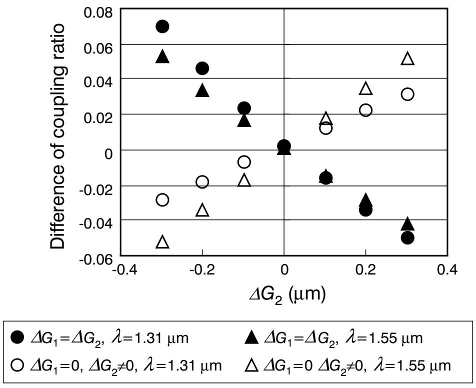

Figure 4 Variation in coupling ratio in WINCs with different DC gap.

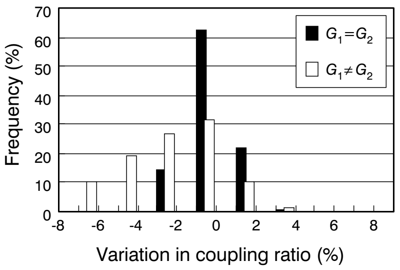

Figure 5 1.31-μm coupling ratio distribution with same and different DC gap.

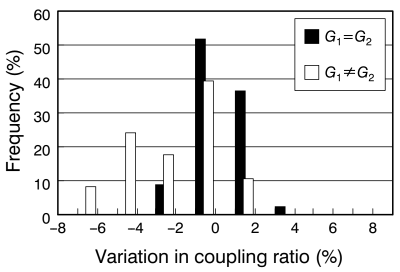

Figure 6 1.55-μm coupling ratio distribution with same and different DC gap.

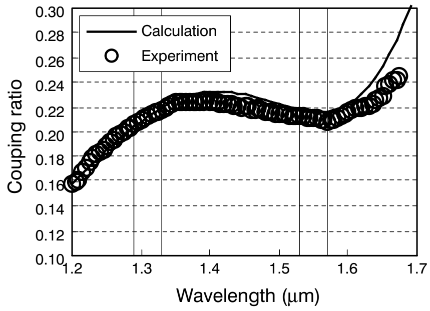

Figure 7 Wavelength-dependence of coupling ratio.

Figure 7 shows a comparison between the wavelength dependence calculated for the design and that obtained experimentally for the devices we fabricated. There was extremely good agreement between results for the design and for the fabricated devices.

As can be seen from the above, the design allows high-yield fabrication of WINCs even when processing was inconsistent. Modules were also made using these chips, and it was confirmed that there was no problem in terms of reliability.

2.2 Splitters

Splitters are an indispensable component of PON systems, and depending on subscriber conditions or cable length, various types of splitter--1 x 4, 1 x 8, 1 x 16, 1 x 32, etc.--may be used. In terms of their characteristics, they must offer extremely low levels of insertion loss and polarization-dependent loss (PDL). And since they are frequently installed outdoors they must also be relatively insensitive to variations in temperature and humidity. Further a number of PLC devices can be fabricated together, so that these multiple splitters are also integrated, as in 4-arrayed 1 x 8, 8-arrayed 1 x 4, etc.

2.2.1 Developing a Method of Splitter Fabrication

In developing the FTTH splitter described here, we decided to use a silica substrate, with its promise of lower PDL, in preference to the silicon substrates, with which Furukawa Electric has a lengthy track record [4), 5)].

As a development procedure it was possible to use a silica substrate as the under-cladding layer, and, in order to fabricate a low-loss core layer, the conditions for FHD --such as gas flow rate and consolidation temperature-- were optimized. Conditions of core channel etching and for over-cladding layer fabrication were reviewed to find conditions conducive to the fabrication of a low-loss waveguide. Finally prototypes having various types of circuit patterns were fabricated and conditions for optimum characteristics were derived.

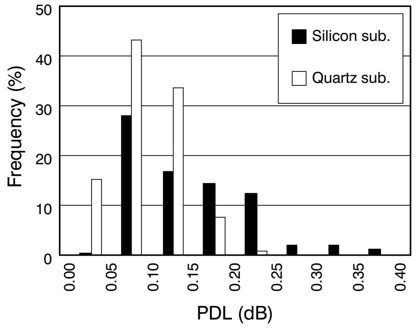

Figure 8 1.31-μm PDL distribution for 4-arrayed 1 x 8 splitters.

Figure 8 compares the PDL distribution for 4-arrayed 1 x 8 splitters using conventional silicon substrates and silica substrates. It can be seen that using the silica substrate gave substantially lower values, both for absolute values and for dispersion.

2.2.2 Results of Splitter Fabrication

Using these process conditions we fabricated 8-arrayed 1 x 4, 1 x 8 and 1 x 16 splitters.

Extremely good results were obtained. For the total number (2080) of 8-arrayed 1 x 4 splitters, the average insertion loss and standard deviation were 6.5 dB and 0.16 dB for the 1.31-μm band, and 6.5 dB and 0.13 dB for the 1.55-μm band; and the average PDL and standard deviation were 0.06 dB and 0.03 dB for the 1.31-μm band, and 0.05 dB and 0.03 dB for the 1.55-μm band.

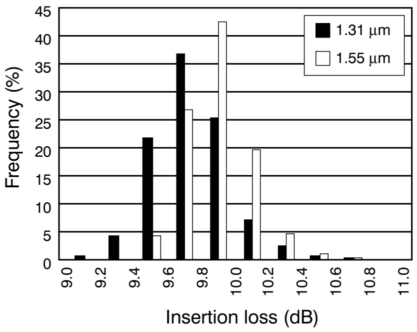

Figure 9 Insertion loss distribution for 1 x 8 splitter.

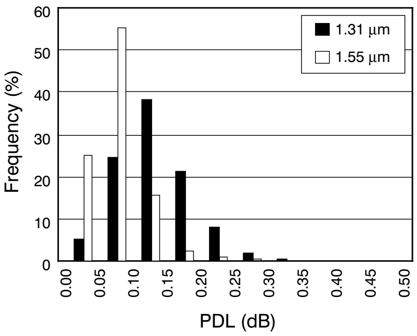

Figure 10 PDL distribution for 1 x 8 splitter.

Figures 9 and 10 show the insertion loss distribution and PDL distribution for a total of 2008 1 x 8 splitters, and satisfactorily low values were obtained. The average insertion loss and standard deviation were 9.7 dB and 0.23 dB for the 1.31-μm band, and 9.9 dB and 0.19 dB for the 1.55-μm band; and the average PDL and standard deviation were 0.13 dB and 0.05 dB for the 1.31-μm band, and 0.07 dB and 0.07 dB for the 1.55-μm band.

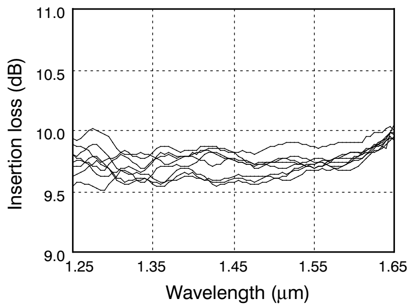

Figure 11 Wavelength dependence of insertion loss for 1 x 8 splitter.

Figure 11 shows the wavelength dependence of insertion loss for a 1 x 8 splitter. Over a wide range, from the 1.31- to 1.55-μm band, low-loss characteristics were obtained.

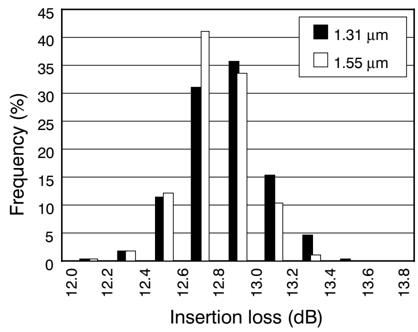

Figure 12 Insertion loss distribution for 1 x 16 splitter.

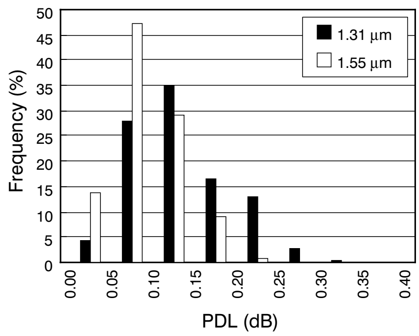

Figure 13 PDL distribution for 1 x 16 splitter.

Figures 12 and 13 show the insertion loss distribution and PDL distribution for a total of 368 1 x 16 splitters, and the results obtained were sufficiently low for practical purposes. The average insertion loss and standard deviation were 12.8 dB and 0.21 dB for the 1.31-μm band, and 12.8 dB and 0.18 dB for the 1.55-μm band; and the average PDL and standard deviation were 0.13 dB and 0.06 dB for the 1.31-μm band, and 0.09 dB and 0.04 dB for the 1.55-μm band. Improvements are on-going to achieve even lower insertion loss and PDL in the future.

3. PLC MODULES

Modules were fabricated using the chips described above and their characteristics were confirmed. There are two sizes, which are Furukawa Electric standards. The compact module accommodates the 1 x 4, 1 x 8 and 1 x 16 splitters, and measures 3.9 x 3.9 mm, with lengths of 38.0, 41.5 and 50.0 mm respectively. The regular module is used for 1 x 32 and 8-arrayed 1 x 4 splitters, and measures 8.0 x 6.4 x 76.0 mm. The former (compact) module is suited to accommodating closures etc. having a low space requirement. Figure 14 is a photograph showing a compact module for a 1 x 8 PLC splitter.

Figure 14 Compact 1 x 8 PLC splitter module.

The method used in fabricating the modules is to join a fiber array, in which fibers are precisely positioned by means of glass V-grooves, to the chip using a UV curable adhesive designed for fiber-optic components. The whole is then enclosed in a case to protect the adhesive joint from ambient conditions. The end faces of the fiber array and chip are treated to prevent optical loss or reflection.

The chips developed in this project are also of a size that can be accommodated in one or other of the modules described above, and using the above method the 1 x 8 splitter can be packaged in the compact module and the 8-arrayed 1 x 4 splitter fits in the regular module. As predicted from chip characteristics, module characteristics for insertion loss and PDL were satisfactory, and return loss averaged 55.6 dB for the 1 x 8 splitter modules and 56.4 dB for the 8-arrayed 1 x 4 splitter modules. Good reliability was also demonstrated, with a loss variation of no more than ±0.1 dB over a temperature range of −40 to +85˚C.

4. RELIABILITY TESTS

Because of the overriding importance of the long-term reliability of components for use in telecommunications systems, reliability tests were carried out both on PLCs using silicon substrates and on those using silica substrates. Here we report on the reliability of 8-arrayed 1 x 4 splitters that use silica substrates.

In reliability tests for testing individual chips, a pressure cooker test was carried out under conditions of 120 °C, 100 % RH for 100 hrs (equivalent to 85°C, 85 % RH for 8000 hrs), and it was confirmed that no external cracking or breakage occurred. Chip reliability was further confirmed by the fact that variations in insertion loss and PDL before and after the test were less than 0.1 dB.

The PLC modules were also subjected to reliability tests in accordance with Telcordia GR-1221 and GR-1209, with the results shown in Table 1. Passes were achieved for all tests confirming that the modules have high reliability.

Table 1 Reliability test results.

Test	Conditions	Time	Max loss deviation (dB)	Pass/ Fail
Temperature-humidity cycling	−40 to +85°C, 10% to 80%RH	42 cycle	0.07	Pass
Water immersion	+43°C, pH 5.5	168 h	0.11	Pass
Fiber and cable retention	0.45 kg, 5 s, 3 times		0.19	Pass
Mechanical shock	5 times, 6 directions, 500 G, 1 ms		0.10	Pass
Vibration	20 G, 20~2000 Hz 4 min/cycle 4 cycle/axis		0.09	Pass
Damp heat (non-hermetic)	85°C/85%RH	2000 h	0.23	Pass
Low temperature storage	−40°C	2000 h	0.19	Pass
Temperature cycling	−40 to +85°C	500 cycle	0.22	Pass

As a representative test, Figure 15 shows the variation in insertion loss for a total of 13 8-arrayed 1 x 4 splitter modules in a damp heat test (85°C 85 % RH for 2000 hrs) at the elapse of 336, 1000 and 2000 hrs. It shows the port exhibiting the greatest increase in loss among the loss variations on 32 ports, 1 module. It can be seen that characteristics remained stable at all times, and that reliability was high at high temperature and relative humidity.

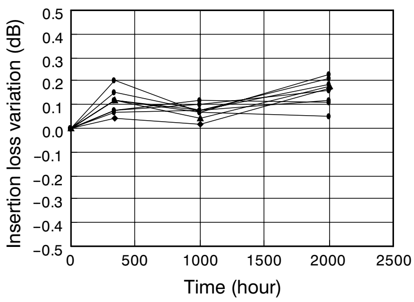

Figure 15 Variation in insertion loss for 8-arrayed 1 x 4 splitter module in damp heat test.

5. CONCLUSION

WINCs and 1 x 4, 1 x 8 and 1 x 16 splitters for FTTH services have been developed using PLC technology.

The possibility of fabricating with good characteristics and high yield has been confirmed. The results of reliability tests were also good, completing the device development. It is proposed in future to apply this technology to the development of other products, such as 1 x 32 splitters or WDM couplers for FTTH service applications.

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