Waveguide Bragg Grating for Fault Localization in PON

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Abstract: Femtosecond laser direct inscription is a technique especially useful for prototyping purposes due to its distinctive advantages such as high fabrication accuracy, true 3D processing flexibility, and no need for mold or photomask. In this paper, we demonstrate the design and fabrication of a planar lightwave circuit (PLC) power splitter encoded with waveguide Bragg gratings (WBG) using a femtosecond laser inscription technique for passive optical network (PON) fault localization application. Both the reflected wavelengths and intervals of WBGs can be conveniently tuned. In the experiment, we succeeded in directly inscribing WBGs in 1×4 PLC splitter chips with a wavelength interval of about 4 nm and an adjustable reflectivity of up to 70% in the C-band. The proposed method is suitable for the prototyping of a PLC splitter encoded with WBG for PON fault localization applications.

Keywords: planar light circuit; power splitter; waveguide Bragg gratings; femtosecond laser; optical network fault localization

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1 Introduction

Fiber-to-the-x (FTTX) technology has made rapid progress in recent decades thanks to the adoption of passive optical network (PON) technology. This technology can effectively reduce the number of fiber channels and eliminate the need for power supply to transmission devices, resulting in low-cost and high-performance solutions.

In a PON system, the network structure is complex, with a large number of users scattered across various locations. More than one-third of network failures are caused by fiber damage[1], which is difficult to locate and repair. As a result, real-time fault localization in the PON system is an important issue that directly impacts the quality of network service and the cost of network maintenance.

Several technologies have been developed for failure detection and localization[2 – 3]. Among them, optical time-domain reflectometry (OTDR) is the most widely used one due to its versatility and convenience. OTDR characterizes fibers using power traces of fiber-backscattered signals, which can be used to extract information and localization related to network failures[4]. However, it is difficult to directly detect failures using OTDR in a point-to-multiple-point topological network due to the superposition of the backward signals. Researchers have improved the conventional OTDR method to distinguish different branches in PON by installing film-type filters as reflectors on optical network units (ONU) and comparing the measured signals with a standard signal[5]. However, this method will inevitably increase the complexity of both the operation and maintenance of ONUs located at the end-user side, which are inconvenient to access and are the most devices in the whole system.

As a result, realizing fault localization before reaching the ONUs is desirable. Fiber Bragg grating (FBG) encoded planar lightwave circuit (PLC) splitters have been proposed to overcome this problem[6 – 7]. Periodic coding schemes have been proposed[8 – 9], which use a pair of FBGs with different reflectance connected by a piece of fiber to generate the periodic codes. A centralized PON fault localization scheme based on optical coding has also been proposed[10], deploying an optical encoder containing a series of FBGs of different wavelengths in front of the user. This scheme achieved a small correlation

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distance and a low multiple-customer interference probability. Another FBG-based OTDR scheme involves probing the signal of a tunable OTDR reflected by the FBGs placed in front of the customers. However, the disadvantages of using FBG-based OTDR solutions for PON fault localization are obvious because the fabrication process for FBG arrays or ribboned FBGs is complicated and not suitable for mass production, which implies difficulty in cost reduction. Moreover, the poor correlation characteristic of FBG-based OTDR solutions increases the difficulty of the recognition process[11].

Recently, a remote coding scheme for PON fault localization using waveguide Bragg gratings (WBGs) in power splitters fabricated by PLC technology has been proposed[11]. Multiple cascaded gratings written on the branches of different stages of a PLC-based splitter can be used to generate the corresponding optical codes. Fig. 1 shows how the PLC chips integrated with WBGs realize the remote coding for the PON fault localization system. The first stage splitters reflect four different wavelengths of λ_1, λ_2, λ_3, and λ_4, and the second stage splitters reflect four wavelengths of λ_5, λ_6, λ_7, and λ_8, resulting in 16 different combinations such as $\lambda_1\lambda_7$ and $\lambda_3\lambda_8$ to determine the optical path where the ONU is located. The key advantage of using WBGs encoded power splitters for PON fault localization is their potential for mass production at the wafer level. This is the most effective way to cut cost, which is the most critical point for PON applications. There are other advantages such as easy installation and maintenance, compact size, and no need for additional devices or components. However, the fabrication of complex Bragg gratings on chip-level or even wafer-level PLC devices using conventional UV exposure assisted with hydrogen loading technique is difficult, high-cost, and time-consuming for prototype device fabrication and system-level validation tests.

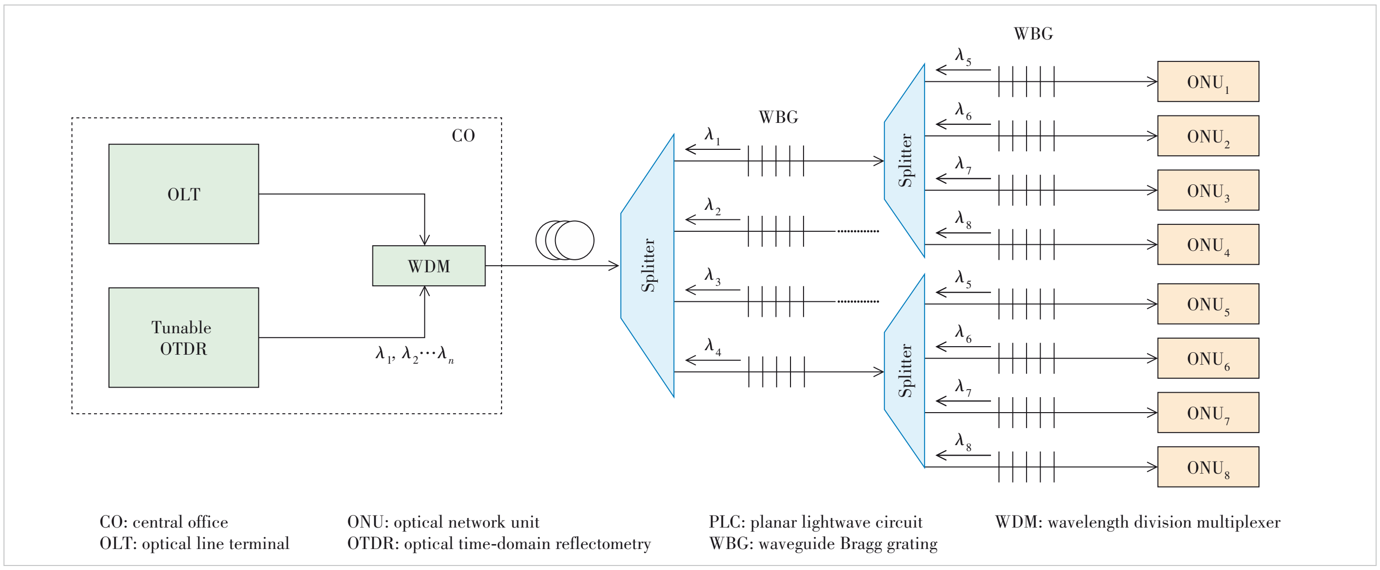
In this paper, we propose a femtosecond laser direct inscription technique for the fabrication of prototype PLC splitters encoded with WBGs for passive optical network fault localization applications. Reflected wavelengths, their intervals of WBGs, and reflectance can be conveniently tuned by adjusting parameters such as period, length, and refractive index modulation of the WBGs. In the experiment, we succeeded in directly inscribing WBGs in the 1×4 PLC splitter chips with a wavelength interval of about 4 nm and an adjustable reflectance of up to 70% in the C-band. The proposed method is suitable for prototyping PLC splitters encoded with WBGs for PON fault localization applications.

2 Fabrication and Evaluation

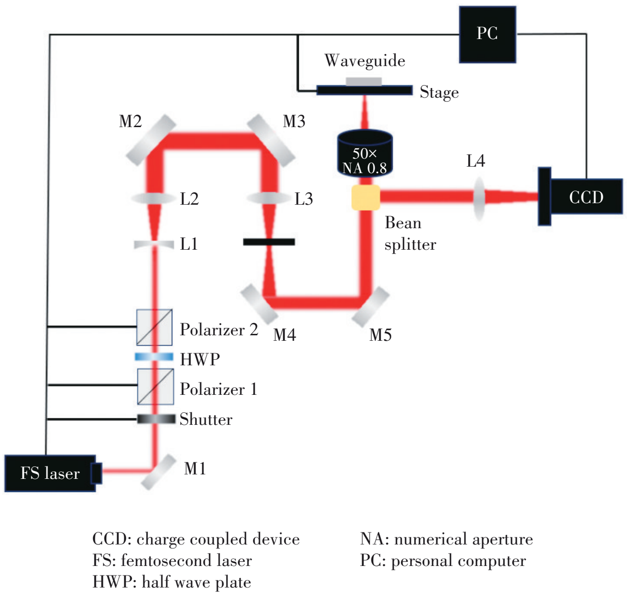
We utilized customized single-channel PLC waveguide chips and 4-channel PLC chips with splitter structures for our experiments. The dimensions of four-channel PLC chips are about 30 mm in length, 3 mm in width, and 2.5 mm in height. There is a comparatively long straight PLC waveguide after the splitter structure and a partly removed cover glass, for waveguide Bragg grating inscription purposes.

The schematic of the femtosecond laser process system and its picture for WBG inscription in PLC chips are shown in Figs. 2 and 3, respectively. The femtosecond laser operates at a wavelength of 515 nm with a pulse duration of 350 fs and a repeating rate of 25 kHz. During inscription, the laser moves at a speed of 50 μm/s. The incident femtosecond laser light is reflected by a total reflection mirror and focused into the center of the waveguide structure of the PLC chip through a 50× objective lens. By optimizing the moving speed, pattern and distance of the displacement stage, laser light can scan over the waveguide and inscribe desirable Bragg gratings on the waveguide in PLC chips.

The pitch Λ of WBG can be represented by $\lambda_B = 2n_{eff}\Lambda$, where λ_B is the Bragg wavelength and n_{eff} is the effective re-

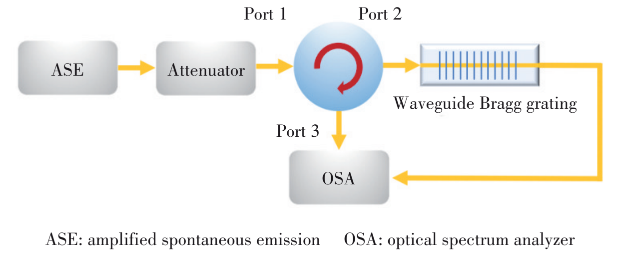


▲**Figure 1. Passive optical network (PON) fault localization using PLC splitter encoded with WBG**

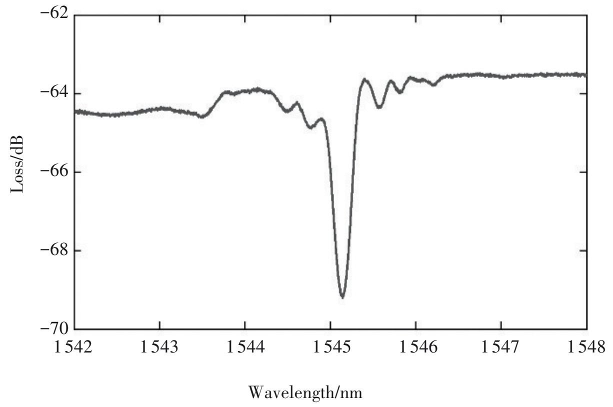


▲ **Figure 2. Femtosecond laser process system for waveguide Bragg grating (WBG) inscription in planar lightwave circuit (PLC) chips**

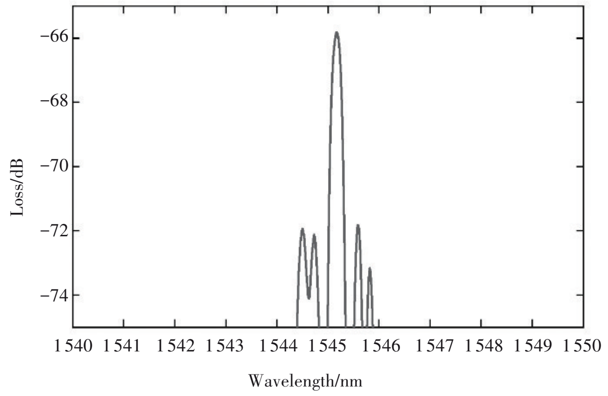
▲ **Figure 3. Picture of femtosecond laser process system**



▲ **Figure 4. Measurement setup for transmitted and reflected optical spectra**



▲ **Figure 5. Measured transmitted spectrum of single-channel waveguide Bragg grating (WBG)**



▲ **Figure 6. Measured reflected spectrum of single-channel waveguide Bragg grating (WBG)**

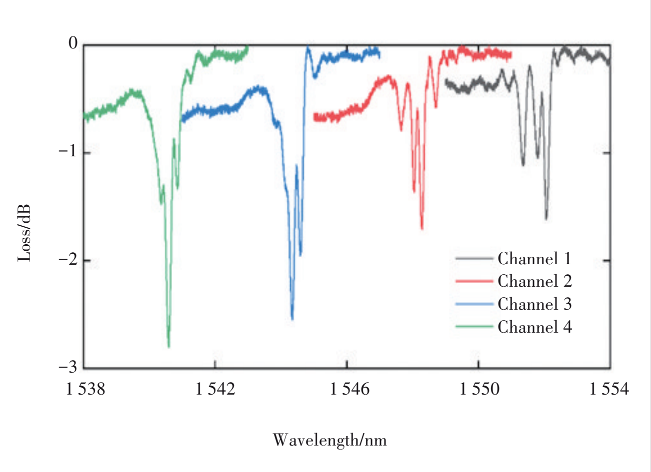
fractive index of the waveguide in the PLC splitter. In our case, the periods of the waveguide Bragg gratings inscribed on channels 1, 2, 3, and 4 are 1.609 μm, 1.605 μm, 1.601 μm and 1.597 μm, respectively. The length of the inscribed grating is 3 000 periods, which is approximately 4 800 μm. During the inscription process, the transmitted spectra of the waveguide could be observed in real time to optimize the inscription parameters.

By optimizing both displacement and aberration correction, we successfully fabricated single-channel WBG and 4-channel WBG in PLC splitters, respectively, with different reflected wavelengths and differently designed reflectance.

The measurement setup for transmitted and reflected spectra is shown in Fig. 4. The transmitted and reflected spectra can be obtained from port 2 and port 3, respectively. The measured transmitted and reflected spectrum of the single-channel WBG is shown in Figs. 5 and 6. The reflected wavelength of WBG is 1 545.1 nm with a reflectance of about 70%, and its 3 dB bandwidth is about 0.3 nm. The main parameters and their transmitted spectra of the four-channel PLC splitter are shown in Table 1 and Fig. 7. The reflected wavelengths of the four channels are intended to be 1 552 nm, 1 548 nm, 1 544 nm, and 1 540 nm respectively, with a negligible wavelength shift up to 0.5 nm. The reflectivity of Channels 1 and 2 is about 30%, while that of Channels 3 and 4 is about 40%. Their 3 dB bandwidths are varying from 0.5 nm to 0.9 nm. The reflected wavelength of the

▼Table 1. Measured results of four-channel PLC splitter

Channel No.	Reflectance/%	Reflected Wavelength/nm	3 dB Bandwidth/nm
1	28	1 552.2	0.8
2	29	1 548.3	0.5
3	40	1 544.4	0.9
4	45	1 540.7	0.5

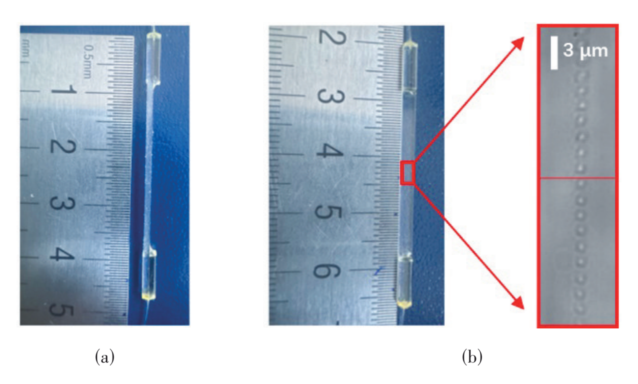


▲ Figure 7. Measured transmitted spectra of 4-channel waveguide Bragg grating (WBG) splitter

single-channel PLC waveguide remains the same at 1 545.1 nm and the measured fluctuation in reflectance is within 0.2 dB under different polarization states, which implies that WBG is not sensitive to polarization. Pictures of the fabricated prototype PLC splitter encoded with WBG are shown in Fig. 8. A microscope graph of WBG structure is also shown in the inset of Fig. 8(b).

3 Conclusions

We implement a femtosecond laser direct inscription technique to fabricate prototype PLC splitters integrated with WBGs for PON fault localization application. By manipulating parameters such as the period, length, and refractive index modulation of the WBGs, we can effectively control the reflected wavelengths and their intervals. Our experimental results demonstrate the capability to directly inscribe WBGs into PLC splitter chips, achieving a wavelength interval of approximately 4 nm and a reflectance of up to 70% in the C-band. This method is suitable for prototyping PLC splitters encoded with WBGs for PON fault localization.



(a)

(b)

▲ Figure 8. Fabricated prototype waveguide Bragg grating (WBG) in planar lightwave circuit (PLC) chip: (a) side-view; (b) top-view

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Biographies

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