Optical Fiber Tags Based on Encoded FBG Array

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Abstract: We proposed an optical fiber tag for identifying the massive passive optical networks, which were encoded by the FBG array with 7 wavelengths and 5 intensity grades, and achieved 5^7 optical tag identification. © 2024 The Author(s).

1. Introduction

The invention of optical fiber communication technology has narrowed the distance between people and countries, making our life informatization and more diversified. As the last kilometer of the information transmission channel, the passive optical network (PON) is a bridge for users to enter the backbone network. However, with the development of passive optical networks, massive optical fibers have been laid everywhere, which has made the management and maintenance of optical networks even more difficult [1]. It is a big challenge to identify each fiber cable, due to their all-identical characteristics [2]. There are serval techniques to identify differentiate optical fiber links in the optical distribution network (ODN) system, such as QR codes and pre-connection techniques which both belong to physical tags. And digital intelligence is an important direction for the next generation of ODN [3]. Huawei Technologies Co., Ltd has reported the "Fiber Iris" to enable intelligent operation and maintenance of ODN [4]. Optical fiber has a small size, and transparent feature, which makes it difficult to print tags outside the fiber as identity labels. However, we could use the interferometric lithographic technology to achieve the optical tag. It is well-known that the fiber Bragg grating (FBG) can be inscribed into the optical fiber core by using techniques such as exposure to ultraviolet laser [5] or femtosecond laser pulses [6], in which the reflection signal can provide information about the position, wavelength, and reflection intensity of grating. Recently, FBGs Co. has proposed optical fiber tags based on FBG arrays [7]. It achieves binary encoding by employing identical gratings prepared using the Draw Tower Grating (DTG) technique and decodes with Optical Time-Domain Reflectometry (OTDR). Fiber tags based on identical gratings can be rapidly fabricated. However, due to the limitations in the spatial resolution of OTDR, the large spacing between adjacent gratings results in a long length for the entire encoding region. Cai et al. reported a miniaturized encryption optical fiber tag based on a point-by-point femtosecond laser pulse chain inscription method [8], which can be multi-dimensionally encoded in position, wavelength, and reflection intensity at centimeter lengths. However, this requires the use of an Optical Frequency-Domain Reflectometry (OFDR) system to demodulate fiber tags, which is expensive and difficult to achieve real-time data analysis. Whether it is based on DTG technology or femtosecond laser, they all have limitations in terms of grating flexibility, efficiency, grating consistency, insertion loss, etc.

In this paper, we proposed a method for the design and automated fabrication of optical tags based on grating array encoding with massive multiplexing capabilities, which expands the original maximum number of binary code multiplexes from 2^n to 5^n. Furthermore, through FBG array multiplexing with 7 wavelengths and 5 levels of reflection intensity, the production of 78,124 optical tags was quickly completed at a 30m/min preparation speed. Using a conventional grating demodulator, the wavelength and reflection intensity information of optical tags can quickly be demodulated. This technical route has a large reuse capacity and low production and demodulation costs.

2. Coding principle of optical tags

FBG arrays offer a variety of multiplexing techniques within a single optical fiber, including time-division multiplexing (TDM) and wavelength-division multiplexing (WDM). TDM FBG arrays employ FBGs of the same wavelength, encoded at specific intervals and distinguished through OTDR or OFDR systems. As shown in Fig.1.(a), the demodulated FBG arrays spectrum can be coded as '1' if there is a reflection peak along a certain distance, and as '0' if there is no reflection peak. Using this encoding form of identical FBGs, if at most 'n' FBGs are written on a single fiber tag, the maximum number of multiplexed fiber tags is 2^n. However, due to the limitation of the spatial resolution of the OTDR, the entire coding area is very long or even tens of meters long. As shown in Fig.1.(b), if FBGs with different wavelengths are used instead of identical gratings, the benefit is that the grating spacing can be reduced to the millimeter level to reduce the length of the entire encoding area. Additionally, conventional demodulation equipment can be utilized for the demodulation of optical tags. Using 'n' FBGs with different wavelengths for encoding, the maximum number of reusable optical fiber tags is 2^n, which is the same as the number of the principle by identical FBGs. However, the tag size and demodulation method have been greatly improved compared with it. As shown in Fig.1. (c), based on WDM, introducing 5-level reflection intensity coding to each FBG can expand the maximum number of reusable fiber tags from 2^n to 5^n.

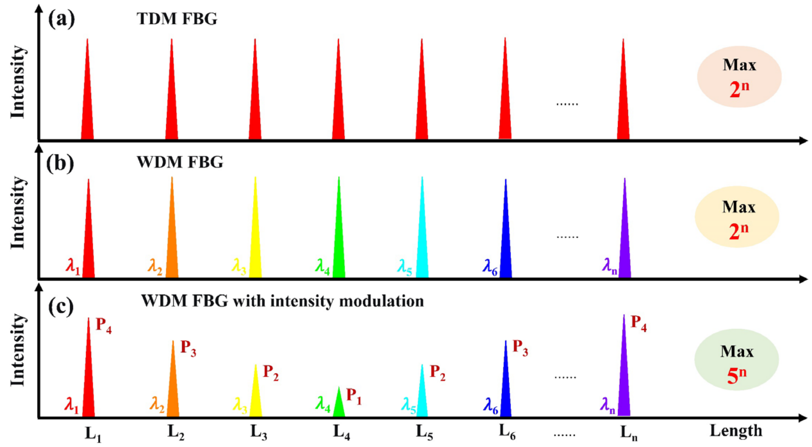

Fig. 1. (a). FBG array encoded by TDM. (b). FBG array encoded by WDM. (c). FBG array encoded by WDM and 5-level reflection intensity.

3. Fabrication of optical tags

The FBG arrays were manufactured with an online automatic inscription system containing a PLC grating fabrication platform and UV-TCF, as shown in Fig.2. (a). According to the preset encoding information, the UV-TCF enters the exposure area with the winding system. The 248nm excimer laser (MLase AG, MLI-500) outputs a single pulse. After being focused by the cylindrical lens, it is directed onto the optical fiber core through the phase mask to realize the grating inscription.

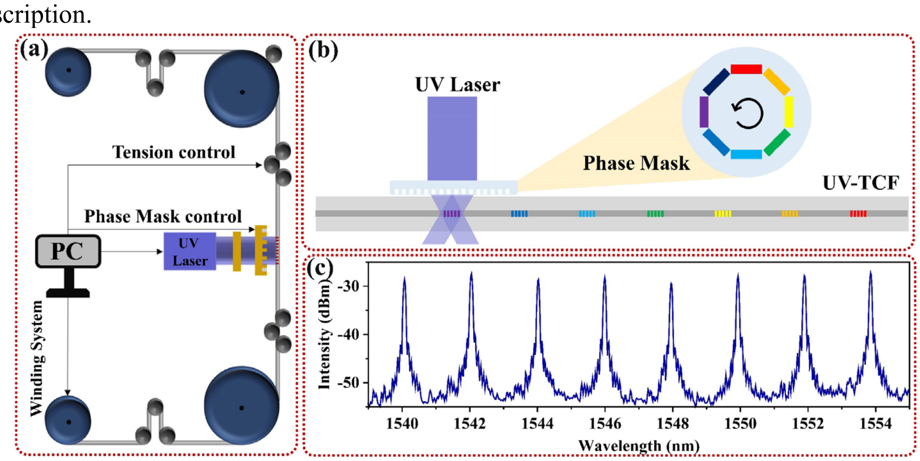

Fig. 2. (a). FBG array online automatic inscription system. (b). Wavelength encoding in the fiber core. (c). FBG array with eight wavelengths with a grating length of 5 mm and a grating spacing of 5 mm.

To achieve continuous wavelength encoding in the fiber core, we use a multi-wavelength phase mask, and wavelength switching can be achieved by rotating the phase mask, as shown in Fig.2. (b). The control of laser output power enables the encoding of reflection intensity, with specified output power levels set at 13.5mJ, 10mJ, 6mJ, 3mJ, and 0mJ. These levels correspond to five distinct reflection intensities, and the difference in reflection intensity between adjacent FBGs is approximately 5 dB. The winding system, laser exposure system, Phase Mask switching system, and tension control system are synchronously controlled through the PC to achieve automated preparation. As shown in Fig.2. (c), it is a continuously prepared FBG array with eight wavelengths with a grating length of 5 mm and a grating spacing of 5 mm.

4. Results

Three representative ones from this group of optical tags were selected for analysis, as shown in Figure 3. The encoding schemes for these three optical tags are 1234321, 4342414, and 4030201, respectively. Each tag consists of seven FBGs, with each FBG having a grating length of 5mm and a spacing of 5mm. Additionally, each FBG possesses a five-level distribution of reflection intensity, as shown in Fig.3. (a~c). Regarding the specific parameters of the FBGs, the wavelengths are 1540 nm, 1542 nm, 1544 nm, 1546 nm, 1548 nm, 1550 nm, and 1552 nm. The optical tags are demodulated with an optical sensing interrogator (MICRON OPTICS, sm125), and its reflection spectrum is shown in Figure 3 (d~f). It is evident that the reflection spectra exhibit a high degree of consistency with the designed coding information. The five-level distribution of reflection intensity is as follows: -28 dB, -34 dB, -42 dB, -48 dB, and -56 dB. The substantial difference of more than 5 dB between adjacent intensities facilitates the rapid identification of optical tag spectral coding information.

To visualize the spatial distribution of the FBG array and the dimensions of the coding region, an OFDR system was employed to conduct testing on the optical tags. The results are presented in Figure 3 (g~i). From these test results, it is apparent that the FBG in the optical tag has a length of 5 mm and a spacing of 5 mm. The total length of the coding region for the entire optical fiber tag is 35 mm. Additionally, the 5-level reflection intensity information is manifested.

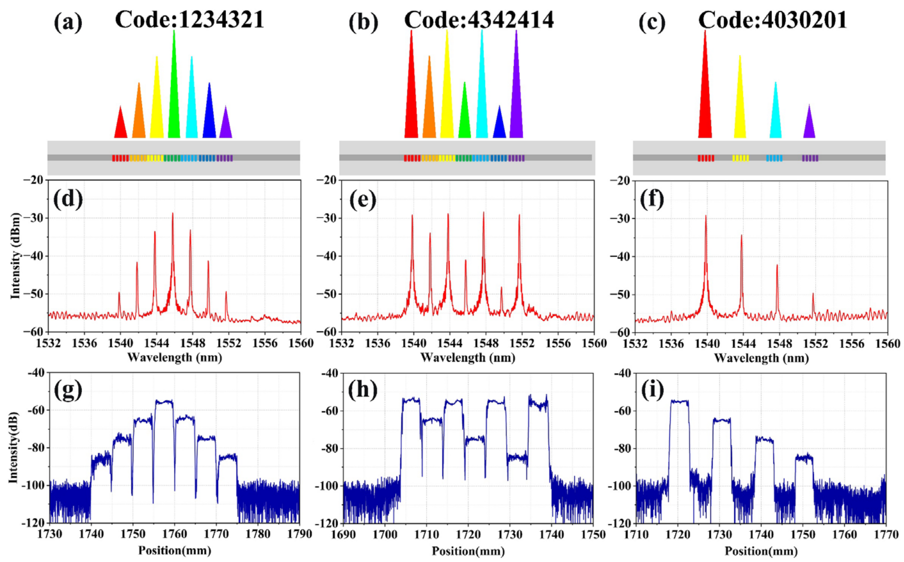

Fig. 3. (a~c). The encoding schemes for three optical tags. (b). The reflection spectrums for three optical tags. (c). The spatial distribution for three optical tags.

5. Conclusions

We have designed a large-capacity optical tag and developed a fast fabrication and demodulation method, which can be employed for encoding and identification of passive optical fiber links. The feasibility of expanding optical tags through a combined encoding of wavelength and reflection intensity in FBG arrays was verified. In particular, the FBG was encoded with 7 wavelengths and 5 levels of reflection intensity, and an online grating system was used to quickly complete the preparation of 78,124 optical tags. The length of the coding area of each optical tag is only 35mm. Moreover, the encoded information of the optical tag can be swiftly demodulated by the optical sensing interrogator in real time.

6. Acknowledgment

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7. References

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