Research Report

250 Mbit/s Bi-directional Single Plastic Optical Fiber Communication System

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Abstract

A bi-directional single plastic optical fiber (POF) communication system has some particularly important advantages for vehicle applications, such as a small connector size, lower installation volume, etc. This paper describes a 250 Mbit/s bi-directional single POF communication system using light-induced self-written (LISW) waveguide modules with a green LED (Light Emitting Diode) and a red LED. Firstly, modules that included a branching LISW waveguide and a newly-designed WDM (Wavelength Division Multiplexing) filter in a small transparent plastic enclosure were fabricated using simple processes. A 250 Mbit/s bi-directional single POF communication system was then demonstrated using modules with a green LED (λ = 495 nm) and a red LED (λ = 650 nm). The measured bit error rates of the system indicated that the feasible length of the POF was more than 20 m. Finally, an on-board camera network for use in vehicles was considered as an application of the system.

Keywords
Optical communication, Plastic optical fiber, Light-induced self-written waveguide, Visible-WDM, LED

1. Introduction

A bi-directional single plastic optical fiber (POF) communication system has some particularly important advantages for vehicle applications. These include a small connector size, high layout flexibility and lower installation volume compared with the use of a dual POF system. Some systems that are capable of realizing bi-directional single POF communication have already been reported. Attempts to use a common wavelength in a bi-directional system caused large amounts of optical crosstalk, resulting in a short transmission length or difficulty in achieving full-duplex operation.[1, 2] On the other hand, visible-WDM (Wavelength Division Multiplexing) systems, which use multiple wavelengths and a WDM filter, can avoid the optical crosstalk problem. However, a visible-WDM system that used optical power splitters suffered from power loss induced by the splitters.[3] Another visible-WDM system that used 45° angled filters and bulk-type optical components required precise alignment processes and/or precise housings to fabricate visible-WDM modules,[4] and applying these systems to vehicle applications was unattractive due to higher system costs. In order to reduce fabrication costs, a light-induced self-written (LISW) technique[5] has been applied to visible-WDM modules that include a branching waveguide and a WDM filter. The feasibility of 125 Mbit/s communication has been demonstrated using LISW waveguide modules that contained one green LED (λ = 525 nm) and one red LED (λ = 650 nm).[6]

In this report, faster communication using visible-WDM modules that include LISW waveguides was examined. In fact, 250Mbit/s communication was demonstrated by using a newly-designed WDM filter and a green LED (λ = 495 nm) developed in-house for high-speed communication.[7] In addition, an on-board camera network for use in vehicles was considered as an application of these modules.

2. A bi-directional single POF communication system

Figure 1 shows a schematic diagram of a bi-directional single POF communication system, which includes two modules that are connected using an in-line POF connector. Each of the modules includes a WDM filter angled at 45° and a branching LISW waveguide. The filter and the waveguide are contained in a miniature transparent plastic enclosure with a pig-tailed POF. The WDM filter has characteristics that enable the transmission of green LED light and the reflection of red LED light. The dimensions of the enclosure are 8 mm in width by 9mm in length by 7 mm in height. Two ends of the branching LISW waveguide are used as optical I/O ports. A green LED and a PD (Photo Diode) are mounted on the I/O ports of one of the modules, while a red LED and a PD are mounted on the I/O ports of the other module.

The process of bi-directional communication is as follows. Light that is emitted by the green LED is coupled into the waveguide and is transmitted through the WDM filter. The light then arrives at the opposite module through the POF and is transmitted through the filter in the second module. Finally, the light is detected by the PD. On the other hand, the light emitted by the red LED is coupled into the waveguide and is reflected by the filter. The light then arrives at the opposite module thorough the POF, is again reflected by the filter, and is then detected by the PD.

3. Experiments

3. 1 LISW waveguide module

Figure 2 shows the process flow that was used to fabricate the LISW waveguide module. Firstly, a dielectric multilayer-type WDM filter was inserted into a slot angled at 45° in the enclosure, and a POF

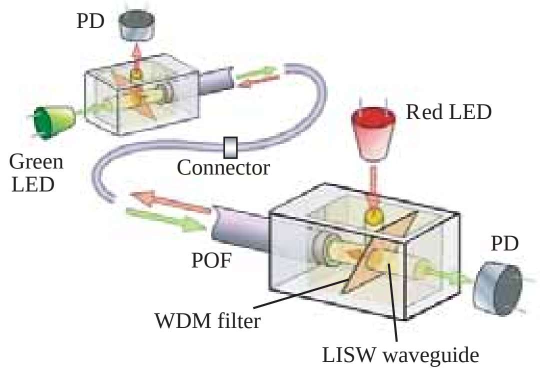

Fig. 1 Diagram of a bi-directional single POF communication system using LISW waveguide modules.

with a core diameter of 1mm (Mitsubishi Rayon Eska-MEGA®, NA = 0.3) was inserted into a socket in the enclosure (Fig. 2(a)). The WDM filter, which was specifically designed to achieve good demultiplexing characteristics for the LEDs that were used in this study, had 85% transmittance for green LED light (λ = 495 nm) and 96% reflectance for red LED light (λ = 650 nm) respectively.[8] The enclosure was then filled with a photopolymerizing resin with a refractive index of approximately 1.51 in order to form the core of the waveguide (Fig. 2(b)). Light from a diode-pumped solid state laser at a wavelength of 457 nm was transmitted through the POF to expose the resin. At the end of the POF, the exposed resin started to harden and grew along the optical axis with a constant diameter, eventually forming the core of the waveguide. The waveguide grew separately in two orthogonal directions, so a branching waveguide was formed that had two optical ports (Fig. 2(c)). The residual resin was removed, and the enclosure was rinsed with isopropanol (Fig. 2(d)). Finally, the enclosure was filled with a photopolymerizing resin that had a refractive index of approximately 1.45. The resin was hardened by UV illumination from all directions using a high-pressure mercury lamp, resulting in the formation of a waveguide cladding layer (Fig. 2(e)).

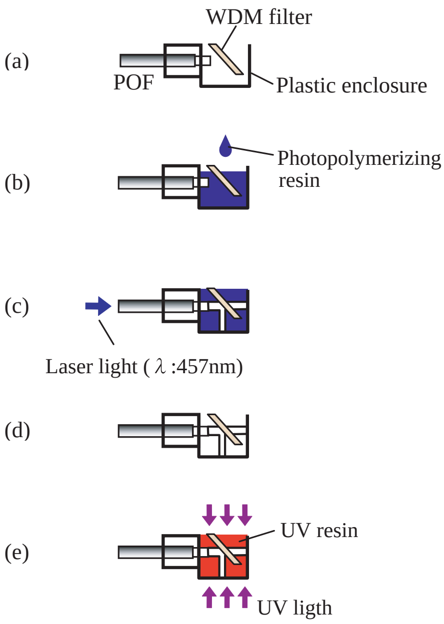

Fig. 2 Process flow used to fabricate a LISW waveguide module. (a) Setting, (b) Resin for core filling, (c) Core forming, (d) Removal of residual resin, (e) Resin for cladding fill and curing.

3. 2 Bit error rate measurements

In order to demonstrate bi-directional single POF communication using the modules, the bit error rate (BER) characteristics of the system were determined. A green LED (λ = 495 nm) that had been developed in-house, a commercially-available red LED (Hamamatsu L7726, λ = 650 nm) and two PIN-PDs that respond at over 250 Mbit/s were mounted on the optical ports of the modules using active alignment processes. At this time, an additional band-pass filter was inserted in front of each of the PIN-PDs in order to avoid optical crosstalk from the local LED. This additional filter will be removed in future designs when the problem of optical crosstalk has been overcome. The coupled powers of the LEDs into the waveguides were -5.7 dBm for the green LED and -1.5 dBm for the red LED under modulated light signals. Each module was mounted on an electrical circuit board including an LED driver circuit and a receiver circuit. **Figure 3** shows the set-up used for the bit error rate measurements. The driver circuit of one of the modules was connected to the pulse-pattern generator (PPG) of a BER tester (Anritsu, MP1632C), which generated signals at 250 Mbit/s, PRBS (Pseudo-Random Bit Sequence) 2^7-1, NRZ (Non-Return-to-Zero), while the receiver circuit of the other module was connected to the error detector (ED) on the BER tester. A variable optical attenuator, which could adjust the input light power to the PIN-PD, was inserted in the POF that connected the modules. The BER was measured in

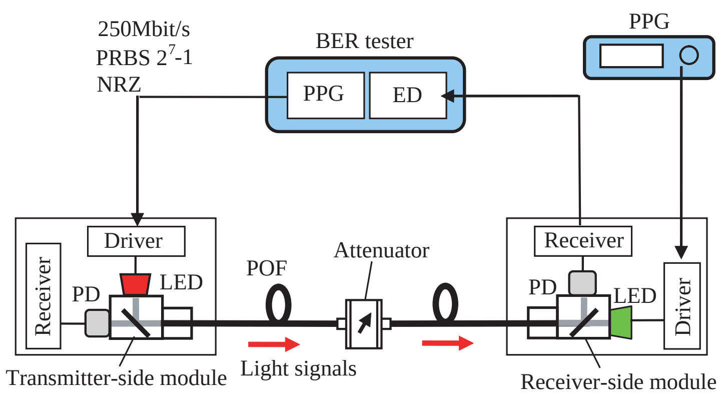

Fig. 3 Experimental set-up for bit error rate measurements.

both half-duplex and full-duplex modes to reveal the power penalty due to crosstalk. In the full-duplex mode measurements, the LED that was mounted on the receiver-side module was operated using an additional PPG under the same signal conditions as the LED on the transmitter-side module.

4. Results and discussion

Figure 4 shows an example of the LISW waveguide module that we produced. It is evident from the figure that a branching LISW waveguide has definitely been formed. The insertion losses of the module were measured at 2.1 dB for the green LED light (λ = 495 nm) and 2.2 dB for the red LED light (λ = 650 nm).

Figure 5 shows the results of the BER measurements. The power penalty due to crosstalk was estimated to be approximately 0.2 dB for each of the red and green LED lights. The input powers into the PD in full-duplex mode at a BER of 10^{-12} (which is the maximum allowed BER in IEEE1394 standard) were -17.4 dBm for the green LED light and -20.6 dBm for the red LED light. These differences in input power are considered to be due to differences in the sensitivity of the PD and the quality of the LED waveforms. These results and the coupled optical powers of the LEDs (described previously) determined that the power budgets of this system would be 11.7 dB for the green LED light and 19.1 dB for the red LED light. Thus, the maximum transmission length of this system was limited by the green LED, bearing in mind that the insertion losses of the system for the green LED and the red LED lights were nearly the same. If a POF were to be inserted between two of these LISW modules in a system using two inline connectors, then the feasible length of the POF can be estimated to be more than 20 m from the total power budget and the individual insertion losses of the two modules (2.1 dB × 2), the two inline connectors (0.8 dB × 2) and the transmission loss of the POF (0.14 dB/m), assuming a 3 dB system margin. This length is considered to be sufficient to cover vehicle applications.

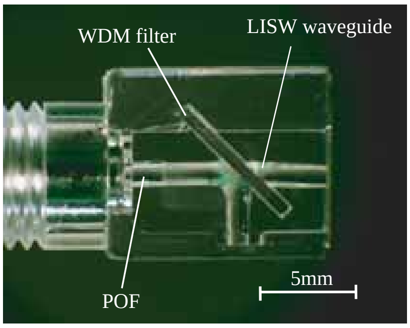

Fig. 4 Example of the produced LISW waveguide module.

5. Application

An on-board camera network for vehicles seems to be a suitable application for a bi-directional single POF communication system, because it requires a higher system data rate to transmit images of the cameras.

Figure 6 shows an example of a possible network

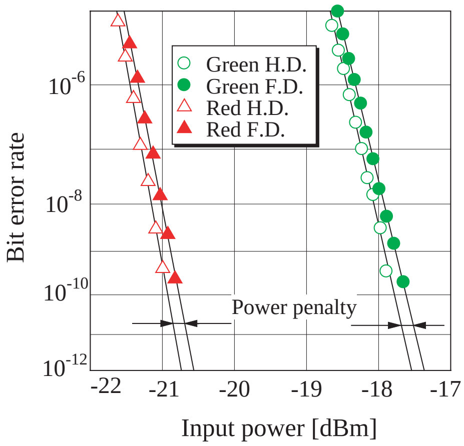

Fig. 5 Results of the BER measurements.

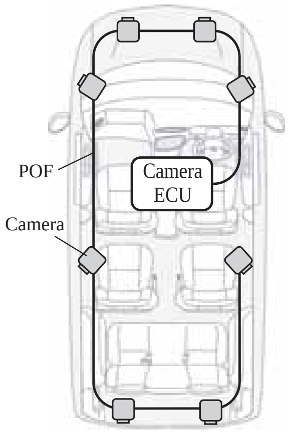

Fig. 6 On-board camera network for vehicles.

configuration. Multiple cameras and a camera ECU (Electronic Control Unit) are connected in a daisy-chain topology using the systems, and the images from the cameras are transmitted to the camera ECU through the POF. **Table 1** shows the required minimum system data rates for the given conditions in terms of the pixel counts of the images and the number of cameras involved. For example, a network for a 250 Mbit/s system over the IEEE1394 protocol can transmit approximately 160 Mbit/s of images and overheads. Consequently, the network is capable of handling eight cameras with a pixel count of 160 × 120, or four cameras with a pixel count of 320 × 240.

A network consisting of eight cameras and a personal computer instead of the camera ECU was tested. As a result, it was confirmed that 160 × 120 pixel images could be displayed on the monitor of the PC. In order to realize a higher data-rate network (e.g. 500 Mbit/s) that would be capable of transmitting higher pixel count images, some improvements to the system are needed, such as higher speed LEDs and lower optical loss in the modules.

6. Conclusion

A 250Mbit/s communication system was demonstrated that incorporated LISW waveguide modules with a newly-designed WDM filter and a green LED (λ = 495 nm). The BER measurements indicated that the feasible length of the POF that could be used was more than 20 m. The use of this system could help to realize low-cost optical networks in vehicles, such as an on-board camera network.

Table 1 Required system data rates for camera networks (30 frames/s, 16bit color depth).

Pixel counts \ Number of cameras	2	4	6	8
160 × 120 (pixels)	18	37	55	74
320 × 240 (pixels)	74	147	221	295
640 × 480 (pixels)	295	590	885	1180

(units: Mbit/s)

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