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Experimental Study of a Power-Over-Fiber Module and Multimode Optical Fiber for a Fishing Camera System

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We determined the feasibility of a fishing camera system using an optical fiber as the fishing line by testing a power-over-fiber (POF) module and multimode optical fiber. Operation of the remote camera module (RCM) without the battery was preferred because the removal of the charging or battery replacement section enabled a waterproof single-body type design. The average efficiency of the photovoltaic power converter (PPC) in the tested POF module was 32.6% at 820 nm, and thus, a high-power laser of at least 1.27 W was required for operating the developed RCM with an electrical dissipation of 413 mW. Because the optical fiber was wound on a fishing reel, composite loss composed of bending and tensile loss occurred. To mitigate the composite loss, we employed a simple holder that showed an improvement in the composite loss of 0.38 dB to 0.8 dB, which was considerably better than the losses without the holder.

Keywords : Power-over-fiber (POF), Photovoltaic power converter (PPC), Bending loss, Tensile tension, Multimode optical fiber, Fishing camera system
OCIS codes : (060.4510) optical communications; (350.4600) Optical engineering

I. INTRODUCTION

Fishing is a vast worldwide leisure industry. The approximately 6.0 million fishermen in Korea comprise the third largest population of fishermen in the world [1]. Recently, several massively multiplayer online role-playing games (MMORPGs) related with fishing such as ChungPung MyungWall and Real Fishing 3D (in Korea) have been developed for entertaining fishing hobbyists. Furthermore, fishing hobbyists have an increased desire for being able to actively view the scenery under the water where they are fishing. For this purpose, several fishing cameras have been developed using copper or coaxial cables for the data transmission [2].

The copper or coaxial lines used for transmitting the video signal in existing fishing or underwater camera systems have diameters of several millimeters. Installing such copper or coaxial lines into a fishing rod would require many sophisticated techniques. Additionally, if the deployed remote camera module (RCM) were corroded from the cable in an unexpected accident, the system would be difficult to repair immediately in the field and would become useless. Therefore, these copper- or coaxial-based systems are expensive, heavy and too bulky to be wound on the reel of a fishing rod for convenient deployment.

To prevent the problems found in coaxial-based systems, a fishing camera using Wi-Fi technology has recently been developed, but the Wi-Fi system can only transmit recorded footage over a limited transmission distance (maximum of 100 m) [3]. The use of optical fiber could increase the transmission distance for high definition video. Underwater camera systems using optical fibers exist; however they are mainly employed in remote operated vehicles (ROVs) for exploring the deep sea [4].

In this study, we proposed a fishing camera system using an optical fiber for data transmission that can be deployed

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Color versions of one or more of the figures in this paper are available online.

by using the optical fiber as the fishing line wound on a fishing reel. We examined the feasibility of this system by studying smartphone connectivity, the efficiency of a power-over-fiber (POF) module for powering the RCM, and losses of the multimode optical fiber that occur when the cable is wound on a fishing reel. With the proposed fishing camera system, the captured video could be transmitted to the user's smartphone via universal serial bus (USB) and shared with family, friends, and other fishing enthusiasts.

II. SYSTEM CONCEPT

The architecture of the overall system is shown in Fig. 1. The system consists of a single-body-type fishing camera module, a base station module (BSM), an external battery, a smart phone, and a fishing rod with a modified fishing reel. The fishing camera module must be completely sealed when it is manufactured to ensure that the module is waterproof. If there is no charging or battery replacement component in the RCM, the single-body-type design is easy to waterproof. Accordingly, the single-body-type RCM received energy from the external battery of the BSM using the POF technique, as shown in Fig. 1. Moreover, in the worst case, if the RCM were lost or failed while fishing, it should be reasonably priced and easy to replace. At the current level of technology, the manufacturing cost of a mass-produced RCM would be roughly \$50 (~\$15 for a complementary metal-oxide semiconductor (CMOS) mini camera, ~\$10 for an electrical-to-optical (E/O) converter, ~\$10 for a photovoltaic power converter (PPC), ~\$10 for other optical and electrical components, and ~\$5 for packaging). In this study, the challenge is determining whether the proposed fishing camera system can obtain good performance in the non-ideal condition of the optical fiber being wound on a fishing reel.

If the fishing camera system were connected to the Internet, as shown in Fig. 2, its function would be widely extended. In the proposed system, the captured video could be transmitted to the user's smartphone for sharing with fishing enthusiasts anywhere in the world. Most social network service (SNS) applications such as KakaoTalk, WhatsApp, and Facebook have group chatting or information sharing functions, so new mobile applications would not need to be developed for the proposed fishing camera system. Moreover, by using the open application programming interface (API) of SNSs, the proposed camera function could be extended for sharing sea temperature, water turbidity, fish species, or the shape of sea bottom based on the global positioning system (GPS) coordinates of the user's phone.

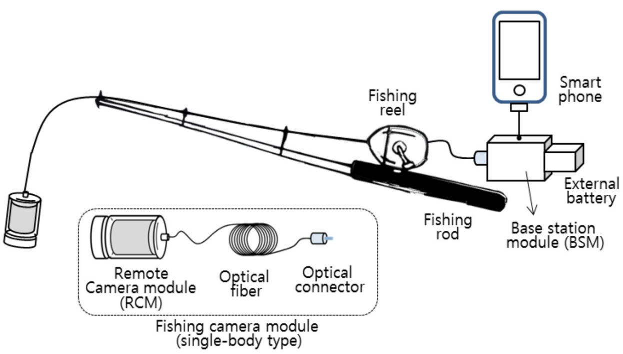


FIG. 1. Conceptual schematic for the proposed fishing camera system.

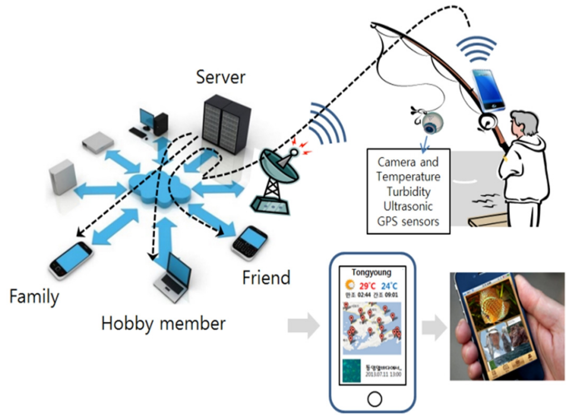


FIG. 2. Overall concept of exchanging the fishing video or other information with acquaintances through SNS servers connected to the Internet.

III. EXPERIMENTS

To analyze the feasibility of the proposed system, we conducted several experiments. First, a fishing camera system for real-time monitoring was tested to transmit the National Television System Committee (NTSC) video signal to a smartphone through a multimode optical fiber. Second, the POF module composed of a PPC and a high power laser was tested to ensure the RCM could be operated without an internal battery. Finally, the composite loss of the multimode optical fiber due to bending and tensile losses was measured, and a simple holder was proposed to mitigate such losses.

3.1. Video Transmission to a Smartphone

Figure 3 shows the experimental setup of a fishing camera system connected to a smartphone. The NTSC video signal generated from the camera was converted to an optical signal by the E/O converter, where a waterproof IR camera with charge-coupled device (CCD) type sensor was used and an average optical power of the E/O converter was -5 dBm at the wavelength of 1310 nm. The optical signal was transmitted through the ~30-m multimode optical fiber and entered the NTSC-to-USB converter after optical-to-electrical (O/E) conversion. The optical power budget of the optical path at the carrier-to-noise ratio (CNR) of 50.0 dB was 23.4 dB. Finally, the converted USB signal was input

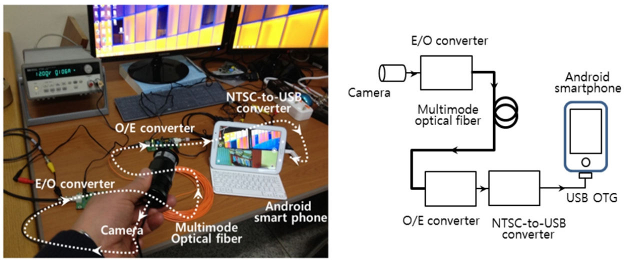


FIG. 3. Experimental setup of a fishing camera system connected to a smartphone for transmitting NTSC video signal.

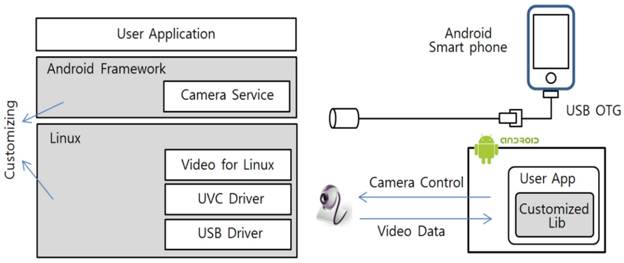


FIG. 4. Implementation of USB isochronous transfer by customizing V4L, UVC driver, and USB driver in the Android framework or Linux kernel.

to the smartphone through the USB on-the-go (OTG) cable. Free Android applications such as CameraFi [5] allows the transmission of a USB video signal to an Android phone or tablet. Such apps require that smartphone is USB OTG capable and has webcam support enabled. Thus, using some simple programming, the fishing camera output can be stored in video or picture format on a standard Android smartphone.

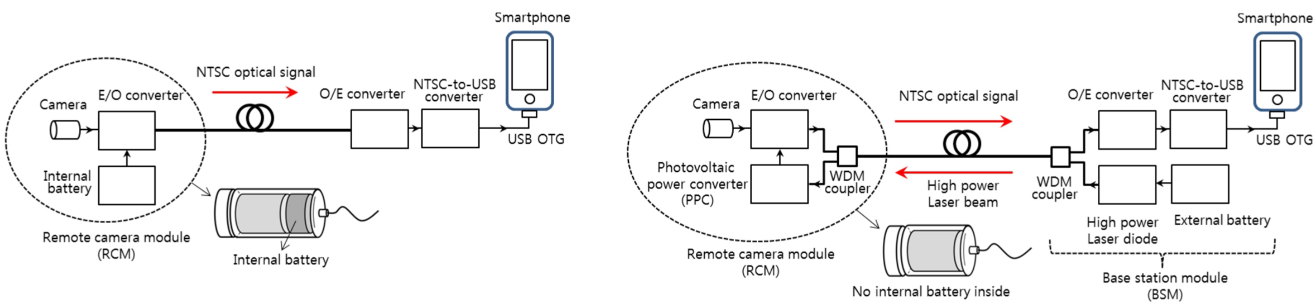
Generally, an Android smartphone can connect USB devices such as USB memory or USB mouse with only an USB OTG cable, which has been supported since Android version 3.1. However, it is currently impossible to connect a general USB camera to an Android smartphone because the Android operating system does not support USB isochronous transfer and the USB video class (UVC) protocol. By customizing Video for Linux (V4L), the UVC driver, and the USB driver in the Android framework or Linux kernel, as shown in Fig. 4, to support USB isochronous transfer, we have succeeded in displaying video on an Android smartphone. To use the USB camera on an Android smartphone, the kernel must be compiled with the V4L2 library. However, many current Android versions already have this library enabled.

Recently, Corning presented a new cable product called USB3.OPTICALTM [6] that can support the USB 3.0/2.0 protocol and has a 5.0 Gb/s transmission speed. This cable could be easily integrated into the proposed system and would return high performance video. The Corning USB3.OPTICALTM cable is made of a ClearCurve VSDN optical cable with bend-insensitive characteristics, which is composed of two optical fibers and one electrical wire. Consequently, this Corning cable would be very expensive, and its diameter would be too thick to be wound on a fishing reel. Therefore, we must consider the use of a simple, less expensive optical fiber for the proposed fishing camera system.

3.2. Test of a POF Module

In simple fishing cameras, internal batteries, as shown in Fig. 5(a), are typically added to supply electrical power to the RCM. However, the internal battery causes difficulties such as short operating time, heavy weight, and imperfect waterproofing. The RCM for the proposed system consisted of an NTSC video camera and an E/O converter, which consumed a total power of 4,800 mW (12 VÍ400 mA) and 4,560 mW (12 VÍ380 mA), respectively, resulting in a total power requirement 9,360 mW. To make 12 V, it is necessary to connect eight AA-size batteries in series. Since the capacity of an AA-size battery is typically 2,400 mAh, the lifetime of the system is approximately 2,400 mAh/780 mA, or 3.1 h. Even with NiCd or LiPo rechargeable batteries, the lifetime would not significantly increase. Moreover, the module itself would become bulky and heavy, and it would not be easy to waterproof structure due to the detachable battery charging or replacement components. Thus, an RCM without any internal battery as shown in Fig. 5(b) is desirable.

For the external battery device, the required 4,800 mW of electrical power will need to be transferred to the RCM



(a) (b)

FIG. 5. Structural schematic of the proposed fishing camera (a) with the internal battery inside the RCM and (b) without the internal battery by using PPC module.

through the optical fiber. The POF technique has been intensively researched [7-9]. Several companies such as Lumentum and MH GoPower sell a POF module of several hundred milliwatts. To determine the feasibility, we tested the commercially available PPC Lumentum PPC-6E, which is a multi-segmented gallium-arsenide (GaAs) device. This single cell PPC normally supplies an open circuit voltage of about 1 V at a wavelength of 810 nm. With six segments connected in series, a total output of 6 V would be feasible.

Figure 6(a) shows the converted electrical power as a function of voltage in the PPC with different optical input powers (0.25, 0.5, 0.75, and 1.0 W at 820 nm). Although the PPC can operate at its maximum optical power of over 2.0 W, the PPC was only measured at a maximum of 1.0 W due to the limited experiment environment. The curves were obtained by sweeping an external load resistance from short to open circuit. Figure 6(b) shows the converted electrical power and the O/E conversion efficiency for various optical input powers. At the injected power of 1.0 W, an electrical power of 322.05 mW is obtained, which yielded an O/E conversion efficiency of 32.2%. The resulting

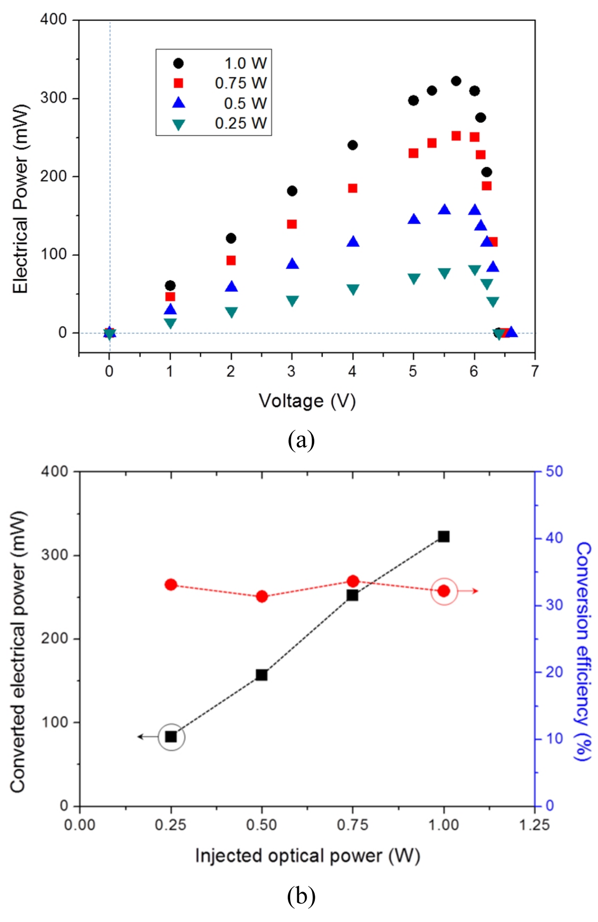


FIG. 6. Measurements of a PPC module for (a) electrical power as a function of voltage in the PPC with different optical input powers (0.25, 0.5, 0.75, and 1.0 W at 820 nm), and (b) the converted electrical power and the O/E conversion efficiency for varying optical input powers.

power was insufficient for the NTSC video camera (4,800 mW) used in the previous experiment (Section 3.1).

However, ultra-low power consumption NTSC video cameras have been recently developed for drones and other applications. In fact, the ultra-low power NTSC camera (MC900-v9) manufactured by 3rd Eye Electronics has a measured power of around 291 mW, which fits well for our purpose. We have also optimized a low-power design for the E/O converter by lowering the operating voltage and the forward current I_f of the laser diode. The designed E/O converter operates at the wavelength of 1310 nm with an average optical power of -12 dBm, which consumes less than 122 mW electrical power. Therefore, a PPC module capable of supplying at least 413 mW (291 + 122 mW) was required to drive the RCM in Fig. 5(b). Since the average efficiency of the tested PCC was 32.6%, as shown in Fig. 6(b), it was necessary to inject at least 1.27 W of optical power to achieve the required 413 mW of electrical power.

However, the loss in the optical fiber used as a fishing line must be considered. For optical video transmission, the loss of a few decibels does not give rise to any problems due to the somewhat larger optical power budget of 16.4 dB, where the receiver sensitivity at the CNR of 50.0 dB is -28.4 dBm. On the other hand, a 1.0-dB loss in a high-power continuous-wave (CW) laser beam into a PPC causes 20.6% power reduction. Therefore, it is desirable to reduce the loss as much as possible, as described in Section 3.3.

If the RCM has the capability of an amphibious drone, namely both flying and submerging, as shown in Fig. 7, the applications will be greatly extended. However, several tens of watts of power must be transmitted using the POF technique. The LaserMotive Company has recently demonstrated flying a drone using a POF module with a 10-W transmitting capability [10] and trying to get a 70-W transmitting module. Amphibious drones have a large number of applications in environmental monitoring, accident surveillance, the first responders' rescue, and so on. In addition, if a three-dimensional first-person view (FPV) camera with two stereo cameras were equipped on the drone, the world could be viewed by 3D video glasses or 3D FPV headsets.

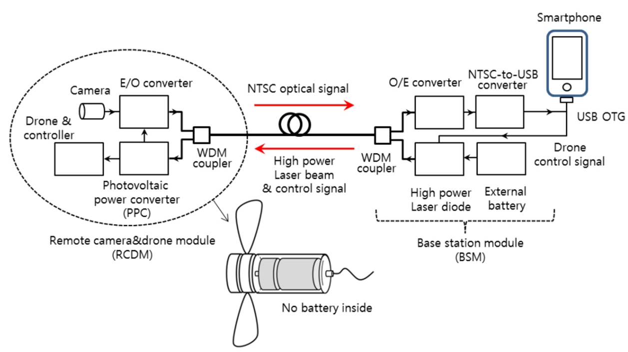


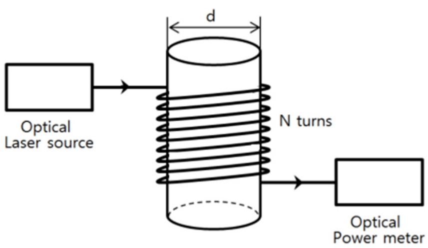
FIG. 7. Structural schematic of the proposed fishing camera with an amphibious drone application using ultra high-powered PPC module.

3.3. Test of a Multimode Fiber Used as a Fishing Line

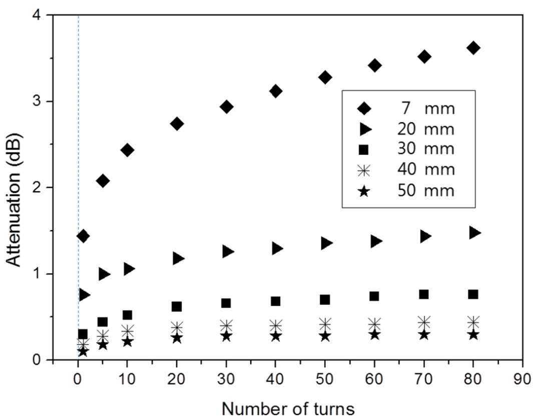
We have experimentally demonstrated the NTSC video transmission of a fishing camera using an optical fiber. For practical uses, several realization problems related with bending and tensile stress of an optical fiber should be solved. Many studies [11, 12] have worked to improve optical fibers using special coatings, structure changes, and etching methods. However, in this study, we focus on the application of a low-cost commercially available optical fiber to the proposed fishing camera system.

First, we conducted a simple measurement to determine the loss characteristics of a multimode optical fiber (Tight buffer 1.6 mm simplex riser cable manufactured by General Cable, 62.5/125 μm, *NA* 0.275 [13]) under bending stress at different diameters for which we prepared several mandrels (i.e., cylindrical rods) to mimic fishing reels. Figure 8(a) shows the experimental setup composed of an optical laser source with 30 dBm (1.0 W) optical power at wavelength of 820 nm, a 100 m multimode optical fiber length, and the mandrel.

Figure 8(b) shows the measurement result for the bending loss as a function of winding numbers *N* according to the mandrel diameters d of 7 to 50 mm. Bending losses were divided by macrobending and microbending, which have different loss mechanisms [14]. Here, only macrobending loss is considered. Bending curvature on the order of 1 mm^{-1} or larger [15] have not been shown to be significant to communication applications. However, for this application, the accumulated bending loss due to many turns must be determined even though the transmission distance is short. When the number of turns *N* is 80, the attenuations are 0.3, 0.44, 0.76, 1.48, and 3.62 dB for the diameters of 7, 20, 30, 40, and 50 mm as shown in Fig. 8(b), respectively.

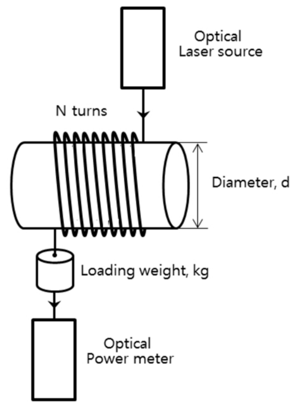


(a)

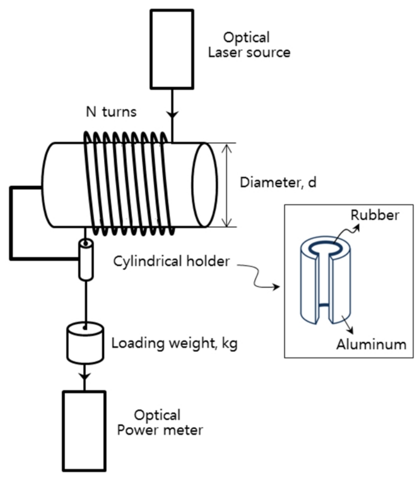


(b)

FIG. 8. (a) Experimental setup for measuring bending loss corresponding to winding turns, and (b) measurement results for the bending loss as a function of winding numbers *N* according to the mandrel diameters *d* of 7 to 50 mm.



(a)



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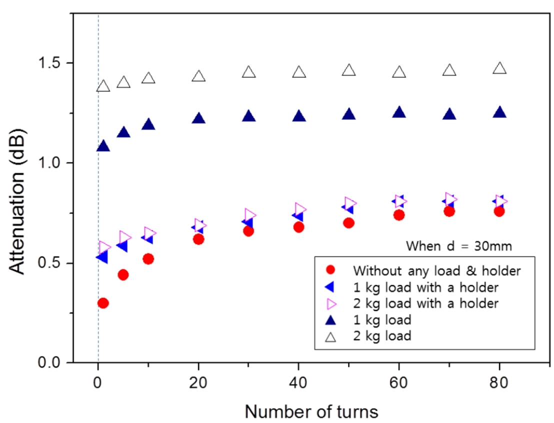

(c)

FIG. 9. Experimental setup for measuring the composite loss corresponding to winding turns *N* (a) with only loading weights, and (b) with loading weights and a holder. (c) Measurement results for the composite loss as a function of winding number *N* according to 1 kg and 2 kg loading weights.

These results fit well with the theoretical analysis that attenuation is proportional to exp (*-R/Rc*). Here, *R* is the bending radius and *Rc* is the critical bend radius for high loss [16], that is given by $Rc = a/(n_1^2 - n_2^2) = a/NA^2$, where a is a diameter of core and NA is a numerical aperture. The tested multimode fiber has a = 62.5 μm and NA = 0.275, and thus *Rc* becomes 0.83 mm. By the rule of thumbs, the bending loss is estimated to increase from 10 times the *Rc*, i.e. 8.3 mm (d = 16.6 mm). As predicted, it can be seen that the loss increases rapidly from d = 20 mm as shown in Fig. 8(b). As the attenuation increases rapidly for reel sizes with diameters of 20 mm or less, larger reel sizes (> 30 mm) were preferred in the proposed fishing camera system.

In the proposed system, not only the bending loss but also the influence on the tensile loss should be considered. To measure the composite loss combined with the bending stress and the tensile loss, the experimental setup as shown in Fig. 9(a) is used with loading weights of 1 and 2 kg. The composite losses result in the increment of 0.78-0.49 dB for 1 kg loading weights and 1.08-0.71 dB for 2 kg loading weights, as shown in Fig. 9(c), while the turns are changed from N = 1 to N = 80. As mentioned before, even a 1.0 dB loss causes 20.6% power reduction, which requires more optical power for the PPC module. To mitigate the composite loss, we proposed a simple holding device (holder) constructed using a grooved cylindrical rod attached with rubber inside the cylinder, as shown in the inlet of Fig. 9(b). The holder is fixed to the mandrel, and the optical fiber is inserted into the groove to firmly hold the optical fiber so that the tensile tension is not transmitted to the mandrel. The tested fiber has specification of 33 Newton (N) maximum tensile load when in-service [13], and it can withstand well the test load (19.6 N = 9.8 m/s^2 Í 2 kg). The length and the diameter inside the holder are 25 mm and about 1.6 mm, respectively. With the holder, the composite losses result in the reduced increment of only 0.23-0.11 dB for 1 kg loading weights and 0.28-0.11 dB for 2 kg loading weights. Using the simple holder, the composite loss can be improved by 0.38 dB to 0.8 dB.

IV. CONCLUSION

In this study, we have successfully verified the feasibility of the proposed fishing camera system using an optical fiber for data transmission. The RCM was connected to a smartphone for a real-time video monitoring through an optical fiber, which was wound on the reel of a real fishing rod. A POF module composed of a PPC and a high-power laser were used to supply power to the RCM without an internal battery. The average efficiency of the tested PCC was 32.6%, and thus, a high-power laser with at least 1.27 W of optical power was required to obtain the necessary 413 mW of electrical power to operate the RCM. When the optical fiber was wound on a fishing reel, composite loss occurred, which was composed of bending loss and tensile loss. To mitigate the composite loss, we employed a simple holder, which improved the composite loss by 0.38 dB to 0.8 dB over that without the holder. For a fishing camera using a commercial available optical multimode fiber, we expect to see satisfactory performance. However, to use the fishing camera under brutal conditions such as tight knotting and folding at very sharp angle, special coating and buffering of optical fiber should be considered.

ACKNOWLEDGMENT

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