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Misalignment Tolerance of Pluggable Ballpoint-Pen Interconnect of Graded-Index Plastic Optical Fiber for 4K/8K UHD Display

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SUMMARY We investigate the influence of launching conditions on misalignment tolerance of pluggable ballpoint-pen interconnects, where graded-index plastic optical fibers (GI POFs) are coupled with ball lenses mounted on their end faces. The lateral-misalignment tolerance of the ballpoint-pen connector decreased with an increase in the driving current of a vertical cavity surface emitting laser (VCSEL) under the center launching condition. This was attributed to the VCSEL multimode oscillation, which increased the connector coupling loss through the higher-order guided mode launching in the GI POF and the resulting output beam expansion in the ballpoint-pen connector. The driving-current dependence of the connector coupling loss could be decreased using offset launchings. For a radial launching offset of 20 μm, we could obtain coupling losses below 1 dB for lateral coupling offsets of $\pm 50\,\mu$m with little dependence on the driving current. This suggests that data transmission quality for misaligned connection of the GI POFs can be improved further by optimizing launching systems for the ballpoint-pen interconnects.

key words: *graded-index plastic optical fiber, ballpoint-pen interconnect, pluggable optical cable, 4K/8K UHD display*

1. Introduction

Recently, ultra-high definition (UHD) displays have been rapidly developed for video formats with 4K (3840×2160) and 8K (7680×4320) resolutions. In Japan, 4K/8K broadcasts through satellites are scheduled for the 2020 Tokyo Olympics and Paralympics, based on a road map announced by the Ministry of Internal Affairs and Communications [1]. This is accelerating research and development of distribution technologies to enable consumers to watch 4K/8K UHD TV at home through satellite, cable television, and internet protocol television. Current UHD displays require uncompressed video data transfer from set-top boxes and smartphones. For 8K video transmission, the data rates can be increased up to ~240 Gb/s [2], suggesting that the interface cables for consumers require extremely high transmission speeds in the upcoming 4K/8K era. Conventional metal interfaces such as serial digital interfaces are not suitable for in-home applications because they require many thick cables and electromagnetic interference prevention methods, without which the throughput of wireless networks can be considerably degraded.

A graded-index plastic optical fiber (GI POF) has been a promising transmission medium for in-home networks because of its flexibility, low installation cost, and high bandwidth [3], [4]. Transmission speeds with a GI POF have been increased up to 40 Gb/s for a length of 100 m with the development of low-dispersive polymers and GI profile control techniques [5]–[8]. Moreover, GI POFs have noise reduction effects, which are closely related to intrinsic mode couplings in GI POFs [9]–[12]. These properties of GI POFs allow for a low-cost optical module without an optical isolator and angled fiber end faces. However, appropriate interconnects of GI POFs for consumer applications have not yet emerged.

Recently, we developed consumer-friendly pluggable interconnects of GI POFs based on ballpoint-pen technologies [13]–[15] enabling easy connection, low-cost production, and fiber end face protection of GI POFs. In the ballpoint-pen interconnect, the output beam from the GI POF is expanded and collimated through the ball lens that is mounted on the fiber end face using ballpoint-pen production technology. In actual optical systems, however, the misalignment tolerance of the ballpoint-pen connector depends on launching conditions because the collimated output beam characteristics are determined by launched guided modes in the GI POF. For a multimode vertical cavity surface emitting laser (VCSEL), the ballpoint-pen connector performance can be influenced by a change in laser driving current, on which oscillation modes of the VCSEL depend. In this paper, the dependence of the misalignment tolerance of the ballpoint-pen interconnect on launching conditions with a multimode VCSEL is investigated. The lateral-offset dependence of the coupling loss is evaluated for different driving currents and launching beam positions to obtain design guideline of the ballpoint-pen interconnect in data communications with multimode VCSELs.

2. Launching System

2.1 Experimental Setup

In the ballpoint-pen interconnect a ball lens is mounted on a GI POF end face for ball-lens coupling of GI POFs, as shown in Fig. 1 (a). The connector production technology is based on the simple and low-cost ballpoint-pen technology. First, a metal ball and an ink case are replaced with a glass ball and a GI POF in a needle-tip type ballpoint pen, respectively. Then, the metal sleeve is punch-processed to keep the distance between the GI POF and the ball lens precise for the output beam collimation. After that, the GI

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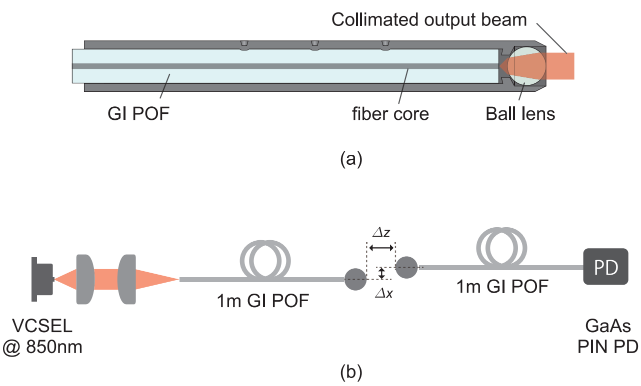

Fig. 1 (a) Schematic structure of ballpoint-pen interconnect. (b) Experimental setup.

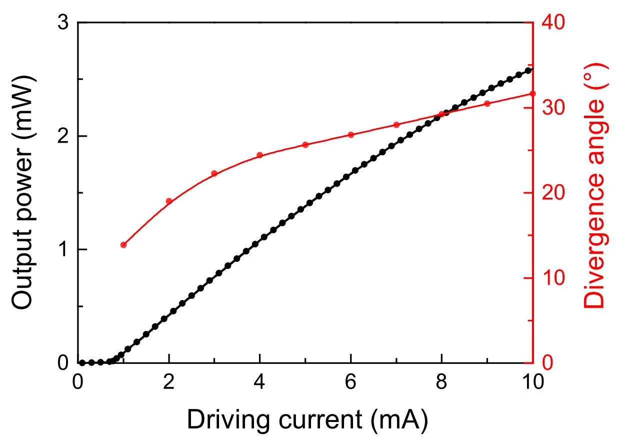

Fig. 2 Output power and far-field divergence angle of the VCSEL as a function of the driving current. The divergence angles are full far-field angles defined in terms of second-order intensity moments [16].

POF is fixed using clamps on the outside of the sleeve. This ballpoint-pen connector significantly increases tolerance for misalignments of the GI POF axes, caused by the expanded and collimated output beam. As shown in Fig. 1 (b), we evaluated coupling characteristics of 1 m GI POFs with the ballpoint-pen connector using a multimode VCSEL with oscillation wavelengths around 850 nm. The ball lenses in the ballpoint-pen connector have a refractive index of 1.51, a diameter of 550 μm, and an effective focal length (EFL) of 407 μm. The core diameter and the numerical aperture (NA) of the GI POF were 80 μm and 0.25, respectively.

Figure 2 shows output power and far-field divergence angle of the VCSEL as a function of the driving current. Higher driving currents resulted in wider divergence angles because of the oscillation of higher-order transverse modes. Because the divergence angles were larger than the NA of the GI POF for driving currents, above ~7.5 mA, we collimated and focused the output beam from the VCSEL to decrease the divergence angles for efficient coupling into the GI POF (Fig. 1 (b)). The NA of the collimating lens was 0.68, which was much higher than those of the VCSEL driven at currents below 10 mA. The focal lengths of the collimating lens and the focusing lens were 3.1 and 6.2 mm,

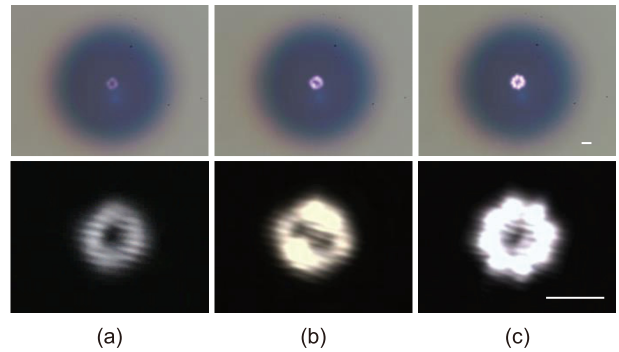

Fig. 3 Microscopic images of focused output beams from the VCSEL on input fiber end faces (top) and the enlarged images of the beam patterns (bottom) for driving currents of (a) 2 mA, (b) 5 mA, and (c) 8 mA. Both the scale bars are 10 μm.

respectively. These allowed for under-filled launching conditions with sufficiently high coupling efficiencies into the GI POF with comparable coupling losses to the Fresnel reflection losses on the input end face of the GI POF.

2.2 Launching Condition with Multimode VCSEL

Figure 3 shows microscopic images of launching beam patterns on input fiber end faces for several driving currents. The blurred images of fiber end faces were due to the chromatic aberration of the imaging system. The significantly-changed beam patterns were observed with an increase in the driving current. The corresponding beam quality parameters of M^2 values were 2.9, 4.3, and 5.0 for driving currents of 2 mA, 5 mA, and 8 mA, respectively. Because of these different beam patterns, higher driving currents result in more guided modes in the GI POF and thus a more expanded beam from the ballpoint-pen connector. This suggests that the misalignment tolerance of the ballpoint-pen interconnect can be influenced by the driving current change of the VCSEL.

Using the ballpoint-pen-coupled GI POFs without the connector misalignment, the relative system transmission loss as a function of the radial launching-beam position on the input end face of the GI POF was evaluated as shown in Fig. 4. The offset launchings increased relative transmission loss through launching of radiation modes and higher-order guided modes for all the driving currents. The radial-offset dependence of the relative transmission loss became stronger for higher driving currents. This was attributed to change of the VCSEL transverse modes with an increase in the driving current. For higher driving currents, radiation modes and higher-order guided modes could be launched for smaller offsets because the launching beams had larger diameters and higher spatial frequencies, as shown in Fig. 3. In this study, the ballpoint-pen interconnect was evaluated for the launching offsets below 20 μm, allowing for evaluation with little effect of the radiation-mode launching.

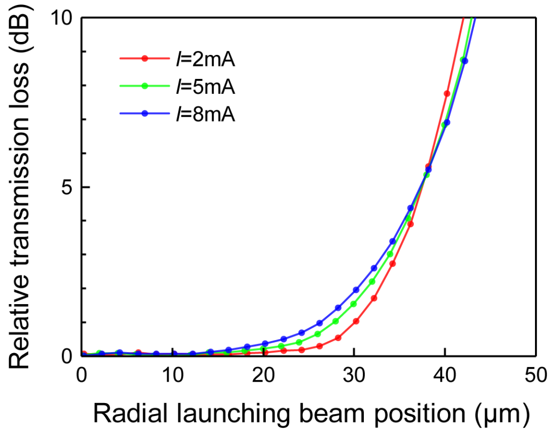

Fig. 4 Relative transmission loss of the coupled GI POFs without the connector misalignment as a function of the radial launching beam position for VCSEL driving currents of 2 mA, 5 mA, and 8 mA.

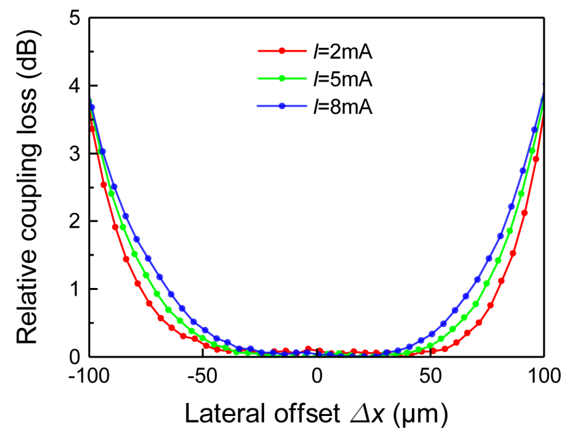

Fig. 5 Relative coupling loss of the coupled GI POFs with the ballpoint-pen interconnect under the center launching conditions as a function of the lateral offset for driving currents of 2 mA, 5 mA, and 8 mA.

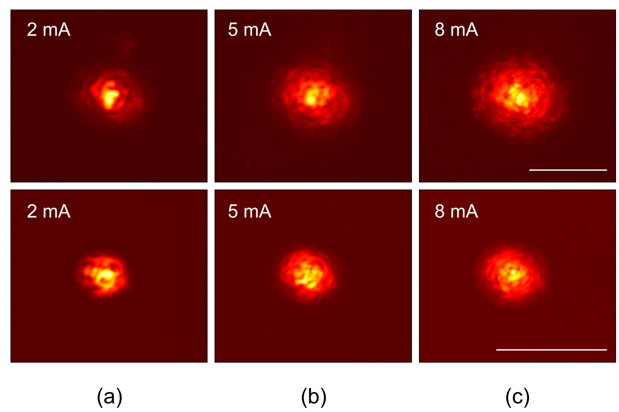

Fig. 6 NFPs (top) and FFPs (bottom) of collimated output beams from the GI POF through the ballpoint-pen connector for the center launchings. The driving currents were (a) 2 mA, (b) 5 mA, and (c) 8 mA. The scale bars are 100 μm (top) and 10° (bottom).

3. Dependence of Misalignment Tolerance of Ballpoint-pen Connector on Launching Condition

3.1 Driving-Current Dependence of Coupling Loss

In actual optical systems, the lateral connector misalignment may be more problematic than the longitudinal connector misalignment, whose tolerance corresponds to a connector separation below a Rayleigh region increased with a square of the beam diameter. In the optical system shown in Fig. 1 (b), the connector separation dependence of the coupling loss was negligible for Δz values below 500 μm, where the lateral-offset-induced coupling loss was barely dependent on the connector separation. In this study, we evaluated the lateral-misalignment tolerance of the ballpoint-pen interconnect for a connector separation of 300 μm.

Figure 5 shows relative coupling loss of the ballpoint-pen connectors as a function of the lateral offset for different VCSEL driving currents under the center launching condition. For all the driving currents, the relative coupling losses were well below 1.0 dB for lateral offsets of ±50 μm. However, the lateral-offset dependence and the resulting tolerance for the lateral offset changed with an increase in the driving current. This suggests that transmitted signal qualities are degraded through changing coupling loss by VCSEL current modulation in actual optical systems with the ballpoint-pen interconnect.

To understand the driving-current dependent coupling losses, we measured near-field patterns (NFPs) of collimated output beams through the ballpoint-pen connector, as shown in Fig. 6 (a). The results showed that the collimated beams expanded more for higher driving currents. The estimated beam diameters (four times the second-order intensity moments) were ~80 μm, ~100 μm, and ~108 μm for driving currents of 2 mA, 5 mA, and 8 mA, respectively. Note that the lateral-misalignment tolerances of the ballpoint-pen interconnect correspond to differences between the collimated beam diameters and the imaginary GI POF core diameter of ~210 μm, which was obtained from the NA of the output GI POF and the EFL of the ball lens [17]. The lateral-offset dependence of the coupling loss is related to the NFP whose electric-field distribution is given by a Fourier transform of that for the GI POF without the ball lens. Therefore, larger collimated beams have higher spatial frequencies corresponding to higher-order guided modes in the GI POF.

Figure 6 (bottom) shows the corresponding far-field patterns (FFPs) of the collimated beams. The collimated beam divergences increased with driving current whereas the collimated beam diameters at the beam waist increased by the higher-order launched modes. The divergence angles (four times the second-order intensity moments) were ~4.2°, ~4.5°, and ~5.0° for driving currents of 2 mA, 5 mA, and 8 mA, respectively. These wider divergence angles for the higher driving current were attributed to higher-order guided mode launching with larger M^2 values, which were 5.4, 7.3, and 8.7 for driving currents of 2 mA, 5 mA, and 8 mA, respectively [18].

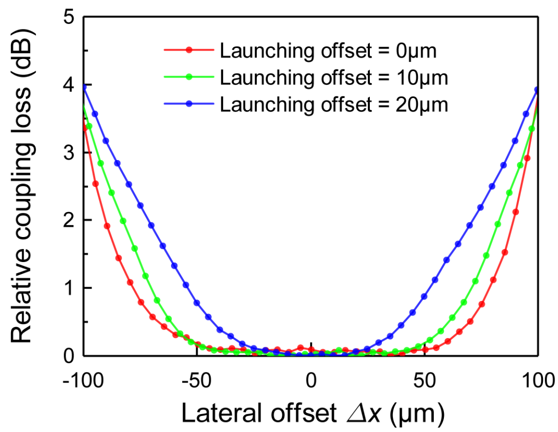

Fig. 7 Relative coupling loss of the coupled GI POFs with the ballpoint-pen interconnect as a function of the lateral offset for the radial launching offsets of 0 μm, 10 μm, and 20 μm. The driving current was 2 mA.

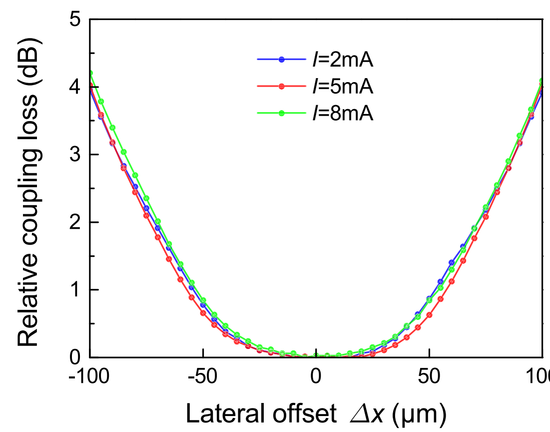

Fig. 9 Relative coupling loss of the coupled GI POFs with the ballpoint-pen interconnect as a function of the lateral offset for driving currents of 2 mA, 5 mA, and 8 mA. The radial launching offset was 20 μm.

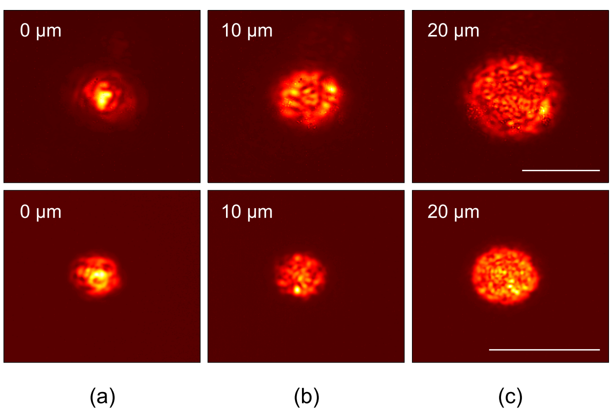

Fig. 8 NFPs (top) and FFPs (bottom) of collimated output beams from the GI POF through the ballpoint-pen connector for a driving current of 2 mA. The radial launching offsets were (a) 0 μm, (b) 10 μm, and (c) 20 μm. The scale bars are 100 μm (top) and 10° (bottom).

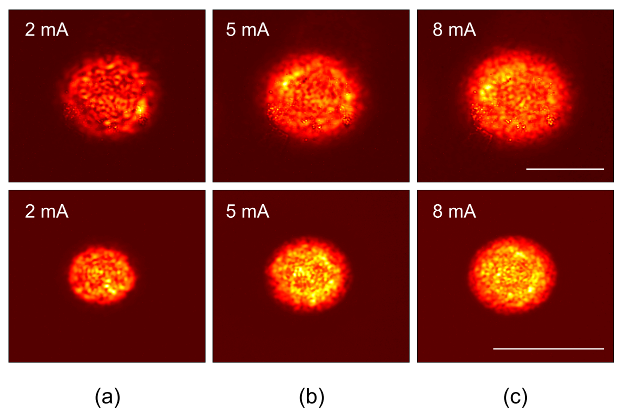

Fig. 10 NFPs (top) and FFPs (bottom) of collimated output beams from the GI POF through the ballpoint-pen connector for the radial launching offset of 20 μm. The driving currents were (a) 2 mA, (b) 5 mA, and (c) 8 mA. The scale bars are 100 μm (top) and 10° (bottom).

3.2 Launching-Offset Dependence of Coupling Loss

The influence of the launching-beam-position change on the coupling characteristics of the ballpoint-pen interconnect was evaluated. Figure 7 shows relative coupling loss as a function of the lateral offset for different launching beam positions. The driving current of the VCSEL was 2 mA. The offset launchings significantly changed the connector-lateral-offset dependence of the coupling loss from the center launching.

Figure 8 shows the NFPs (top) and the FFPs (bottom) of the collimated beams for the launching beam positions. For the radial launching offset of 10 μm, the beam diameter, the divergence angle, and the M^2 value of the collimated beam were ~108 μm, ~5.0°, and 9.0, respectively. By increasing the radial launching offset to 20 μm, the beam diameter, the divergence angle, and the M^2 value were increased to ~136 μm, ~7.7°, and 17.0, respectively. For larger radial launching offsets, higher-order principal mode groups (PMGs) with more guided modes could be selectively launched [19]. This resulted in the collimated beams having more expanded and speckled beam patterns, as shown in Fig. 8 (top). This was reflected in the degraded beam qualities due to higher spatial frequencies of the launched modes by increasing the radial launching offset.

For a radial launching offset of 20 μm, the coupling loss of the ballpoint-pen interconnect barely depended on the driving current, as shown in Fig. 9. Moreover, the coupling losses were kept below 1 dB for the lateral offsets of ±50 μm whereas they were increased compared to those for the center launching. Figure 10 shows the corresponding NFPs (top) and the FFPs (bottom) of the collimated beams for the different driving currents. The driving-current dependence of the collimated beam characteristics was decreased from the center launching. For driving currents of 5 mA and 8 mA, the collimated beams had similar beam diameters of ~156 μm, divergence angles of ~7.8°, and M^2 values of 20.0. These values were also comparable to those for driving currents of 2 mA. These results suggest that we can suppress transmitted signal degradation due to dynamically-changed coupling loss by VCSEL current modulation by applying offset launching techniques.

4. Conclusion

The influence of the launching-condition change on the misalignment tolerance of the ballpoint-pen interconnects of the GI POF with the launching system based on the multimode VCSEL was investigated. For center launching, the lateral-misalignment dependence of the coupling loss was increased with an increase in the driving current, on which the transverse oscillation mode of the VCSEL depended. This was attributed to higher-order launched modes and thus more expanded output beam of the GI POF with the ballpoint-pen connector. Using launching with a radial offset of 20 μm, the coupling losses below 1 dB for the lateral misalignments of ±50 μm could be obtained with little driving-current dependence. This suggests that the data transmission quality for misaligned connection of the GI POFs can be improved further by optimizing launching systems for the ballpoint-pen interconnects.

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References

[1] K. Motohashi, "Media, culture and industry in the 4K/8K smart TV era," New Breeze, vol.26, no.2, pp.5–7, April 2014.

[2] INTERFACE FOR UHDTV PRODUCTION SYSTEMS, ARIB ISTD-B58 Version 1.0, 2014.

[3] Y. Koike, Fundamentals of plastic optical fibers, Wiley, New York, 2015.

[4] Y. Koike and A. Inoue, "High-speed graded-index plastic optical fibers and their simple interconnects for 4K/8K video transmission," J. Lightw. Technol., vol.34, no.6, pp.1551–1555, March 2016.

[5] Graded-refractive-index optical plastic material and method for its production, by Y. Koike and M. Naritomi. (1994). JP Patent 3719733, US Patent 5783636, EU Patent 0710855, KR Patent 375581, CN Patent L951903152, TW Patent 090942, originally filed in 1994.

[6] Y. Koike and T. Ishigure, "High bandwidth plastic optical fiber for fiber to the display," J. Lightw. Technol., vol.24, no.12, pp.4541–4553, Dec. 2006.

[7] A. Polley and S.E. Ralph, "40 Gbps links using plastic optical fiber," Proc. Opt. Fiber Commun. Conf. 2007, OMR5, Anaheim, USA, March 2007.

[8] S.R. Nuccio, L. Christen, X. Wu, S. Khaleghi, O. Yilmaz, A.E. Willner, and Y. Koike, "Transmission of 40 Gb/s of DPSK and OOK at 1.55 μm through 100 m of plastic optical fiber," Proc. 34th European Conf. on Opt. Commun., Brussels, Belgium, We.2.A.4, Sept. 2008.

[9] A. Inoue, T. Sassa, K. Makino, A. Kondo, and Y. Koike, "Intrinsic transmission bandwidths of graded-index plastic optical fiber," Opt. Lett., vol.37, no.13, pp.2583–2585, July 2012.

[10] A. Inoue, T. Sassa, R. Furukawa, K. Makino, A. Kondo, and Y. Koike, "Efficient group delay averaging in graded-index plastic optical fiber with microscopic heterogeneous core," Opt. Express, vol.21, no.14, pp.17379–17385, July 2013.

[11] A. Inoue, R. Furukawa, M. Matsuura, and Y. Koike, "Reflection noise reduction effect of graded-index plastic optical fiber in multimode fiber link," Opt. Lett., vol.39, no.12, pp.3662–3665, June 2014.

[12] M. Matsuura, R. Furukawa, Y. Matsumoto, A. Inoue, and Y. Koike "Evaluation of modal noise in graded-index silica and plastic optical fiber links for radio-over-multimode fiber systems," Opt. Express, vol.22, no.6, pp.6562–6568, March 2014.

[13] T. Torikai, T. Yamauchi, S. Mine, N. Moriya, A. Mitsui, H. Suzuki, Y. Watanabe, M. Kanou, H. Takizuka, T. Toma, and Y. Koike, "Optical I/O connectors employing ball-point pen type optical collimator lenses suitable for plastic optical fiber communications," Proc. 21st Int. Conf. Plastic Optical Fibers, pp.227–231, Atlanta, USA, Sept. 2012.

[14] H. Takizuka, T. Torikai, A. Mitsui, H. Suzuki, Y. Watanabe, T. Toma, and Y. Koike, "A proposal of novel optical interface to transmit 8K-UHDTV for consumer applications," Proc. 18th Microoptics Conf., pp.1–2, Tokyo, Japan, Oct. 2013.

[15] T. Toma, H. Takizuka, T. Torikai, H. Suzuki, T. Ogi, and Y. Koike, "Development of a household high-definition video transmission system based on ballpoint-pen technology," Synthesiology, vol.7, no.2, pp.118–128, May 2014.

[16] P.A. Bélanger, "Beam propagation and the *ABCD* ray matrices," Opt. Lett., vol.16, no.4, pp.196–198, Feb. 1991.

[17] A. Nicia, "Lens coupling in fiber-optic devices: efficiency limits," Appl. Opt., vol.20, no.18, pp.3136–3145, Sept. 1981.

[18] H. Yoda, P. Polynkin, and M. Mansuripur, "Beam quality factor of higher order modes in a step-index fiber," J. Lightw. Technol., vol.24, no.3, pp.1350–1355, March 2006.

[19] R.E. Freund, C.-A. Bunge, N.N. Ledentsov, D. Molin, and Ch. Caspar, "High-Speed Transmission in Multimode Fibers," J. Lightw. Technol., vol.28, no.4, pp.569–586, Feb. 2010.

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