Mode-dependent characterization of photonic lanterns

Citation for published version (APA):

Yu, D., Fu, S., Cao, Z., Tang, M., Liu, D., Giles, I., Koonen, A. M. J., & Okonkwo, C. M. (2016). Mode-dependent characterization of photonic lanterns. *Optics Letters*, 41(10), 2302-2305. <https://doi.org/10.1364/OL.41.002302>

Document license:

TAVERNE

DOI:

[10.1364/OL.41.002302](https://doi.org/10.1364/OL.41.002302)

Document status and date:

Published: 05/05/2016

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Optics Letters

Mode-dependent characterization of photonic lanterns

DAWEI YU,^{1,2} SONGNIAN FU,^{1,*} ZIZHENG CAO,² MING TANG,¹ DEMING LIU,¹ IAN GILES,³
TON KOONEN,² AND CHIGO OKONKWO²

¹National Engineering Laboratory for Next Generation Internet Access System, School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China

²COBRA Research Institute, Eindhoven University of Technology, Eindhoven 5612 AZ, The Netherlands

³Phoenix Photonics, Sarre Business Centre, Canterbury Road, Sarre, Birkington, Kent CT7 0JZ, UK

*Corresponding author: songnian@mail.hust.edu.cn

Received 23 February 2016; revised 13 April 2016; accepted 19 April 2016; posted 20 April 2016 (Doc. ID 259824); published 11 May 2016

We propose and experimentally demonstrate a simple method for characterizing the power transfer matrix of photonic lanterns (PLs) used for mode division multiplexing (MDM) transmission. Due to the optical reflection arising at output facet of the few-mode fiber (FMF), we are able to detect the power at the individual single-mode fiber (SMF) input port and exploit a series of equations based on the theory of energy conservation to obtain mode-dependent characteristics of the PL, including the property of mode selectivity, insertion loss (IL), and channel-dependent loss (CDL). The proposed method is experimentally verified for both the mode selective and the nonmode selective photonic lanterns. © 2016 Optical Society of America

OCIS codes: (060.1810) Buffers, couplers, routers, switches, and multiplexers; (060.2340) Fiber optics components; (060.4230) Multiplexing; (060.2330) Fiber optics communications.

<http://dx.doi.org/10.1364/OL.41.002302>

Recently, mode division multiplexing (MDM) using few-mode fibers (FMFs) [1], together with multi-input multi-output (MIMO) digital signal processing [2], is regarded as a promising solution to further enhance the data-carrying capacity of single optical fiber [3,4]. The critical challenges for MDM implementation are to multiplex and de-multiplex several mode channels with a high contrast ratio, tolerable insertion loss (IL), channel-dependent loss (CDL), and low mode-dependent loss (MDL) [5]. The mode division multiplexers (MMUXs) based on free-space optics usually have severe IL and CDL, limiting their practical applications [6,7]. However, the waveguide-based MMUXs, such as long-period fiber Bragg gratings [8] and PLC-based couplers [9], have relatively smaller IL. Most recently, due to low IL and CDL, photonic lanterns (PLs) emerge as the most promising multiplexing solution. By employing multiple input SMFs that are adiabatically tapered into a single multi-mode fiber (MMF), several modes can be simultaneously launched into the fiber of interest [10]. Recent experiments have demonstrated six spatial and polarization modes multiplexing QPSK signal transmission over 900 km

FMF using PL-based MMUX with low IL and low CDL [11]. According to the fabrication techniques, PLs can be divided into two categories, all-fiber PL [12] and laser inscribed 3D waveguide PL [13]. In view of mode selectivity, there are two forms of PLs, nonmode selective [14] and mode selective [15,16]. For nonmode selective PLs, the modes fully couple at the output of the PL while, for mode selective PLs, most of the power from one input SMF is coupled into one specific mode. Therefore, a compact and easy method for characterizing a power transfer matrix of PL is highly desired, although MDL of the photonic lantern can only be derived from the field transfer matrix. Until now, the field transfer matrix can only be quantitatively characterized, when a multi-port optical vector network analyzer with a spatial-diversity (SDM-OVNA) operating at the reflection mode is utilized, where a swept wavelength interferometer is involved [17,18]. In this Letter, a simple method for characterizing the power transfer matrix, mode selectivity, IL, and CDL of PLs is proposed. By exploiting optical reflectivity, the power at each input SMF is quantitatively determined by the power transfer matrix of the PL. By launching power into each input port independently and detecting the power out of each port, we are able to obtain the power transfer matrix of the PL, as well as corresponding mode selectivity and CDL.

When the input SMFs are adiabatically merged into a single multi-mode core, the launched single-mode field evolves into the modes guided by the FMF, and vice versa. When the light is launched from one input port, the output modal field can be treated as the superposition of several guided modes of the output FMF. Thus, the input power distributes among the modes, each mode possessing a ratio that is defined as mode excitation efficiency. The power transfer matrix of PLs is composed of these mode excitation efficiencies. For a three-mode PL, as shown in Fig. 1(a), the correspondence between the SMF input ports and the output modes is described in Fig. 1(b). We define LP_{01} , LP_{11a} , and LP_{11b} as modes 1, 2, and 3, respectively. The mode excitation efficiency R_{ij} represents the ratio of power launched from port i that is coupled into mode j . The power transfer matrix has the form of Eq. (1),

Fig. 3. Captured output field profiles. (a)–(c) are for Phoenix Photonics 3PL-0140104 when launching power from ports 1–3, respectively. (d)–(f) are for Phoenix Photonics 3PL-0140106 when launching power from ports 1–3, respectively.

modal profile from the output FMF. The experimentally captured modal profiles are shown in Figs. 3(a)–3(c). The detected power from the same input port as the launching one after a circulator is larger than that from other input ports, indicating strong mode selectivity. After numerical calculations, the transfer matrix is shown in Table 1. It can be found that $R_{ii} \gg R_{ij}$ ($i \neq j$), indicating that most of the incident power is coupled to the expected mode. The LP_{01} mode selectivity over LP_{11} modes is 16.80 dB when launching from port 1 while, when launching from ports 2 and 3, the LP_{11} mode selectivity over LP_{01} mode and the spatially orthogonal LP_{11} mode is 16.54 and 14.77 dB, respectively. The IL is 3.67, 4.07, and 4.22 dB, respectively. The corresponding CDL is smaller than 0.55 dB. For a nonmode selective PL (Phoenix Photonics 3PL-0140106), the transfer matrix is shown in Table 1. The corresponding output modal profiles are summarized in Figs. 3(d)–3(f). Weak mode selectivity can be observed from both the calculated transfer matrix and the output modal profiles. The calculated CDL is as high as 2.11 dB.

The proposed method can be quantitatively verified when we cascade two PLs by splicing them at the FMF ends, after adjusting the orientation to realize a mode match. When launching power from one PL, the output power from the ports of the other PL should follow the transfer matrix product,

$$P_{\text{out-PL2}} = T_{3PL-2}^T \cdot T_{3PL-1} \cdot P_{\text{in-PL1}} \quad (9)$$

Consequently, the detected output power from PL 2 is a little different from the calculated values with Eq. (9), due to the perturbation with the error by

$$\text{Error} = \frac{\|P_{\text{out-calculate}} - P_{\text{out-measure}}\|}{\|P_{\text{out-calculate}}\|^{1/2} \times \|P_{\text{out-measure}}\|^{1/2}} \times 100\%, \quad (10)$$

Table 1. Calculated Transfer Matrix of a Three-Mode PL

	Mode 1	Mode 2	Mode 3	PL
Port 1	0.4208	0.0055	0.0033	Mode Selective
Port 2	0.0046	0.3833	0.0039	
Port 3	0.0032	0.0090	0.3662	
Port 1	0.2305	0.0624	0.0182	Nonmode Selective
Port 2	0.0553	0.3446	0.1059	
Port 3	0.0331	0.0556	0.2871	

where $\|\cdot\|$ represents the 2-norm operator. When power is launched from three input ports of PL 1 sequentially, the errors are found to be 1.327%, 2.818%, and 3.104%, respectively. When power is launched from port 1, the error is the smallest because most of the power from port 1 of PL 1 is coupled into the LP_{01} mode whose modal profile changes little under fiber perturbation. When we launch power from PL 2, the final errors are calculated to be 3.525%, 4.859%, and 4.766%, respectively. These data quantitatively prove the rationality of the proposed method. Meanwhile, another quantitative verification method can be done by modal profile overlap integration. By operating overlap integration between the captured modal pattern and analytical equation of the designated LP modes, we can obtain the excitation efficiency of LP_{01} and LP_{11} modes. These excitation efficiencies constitute the power transfer matrix. The measurement error of the power transfer matrix can be calculated with Eq. (10). The errors of the three-port mode selective and nonmode selective PLs under test are 7.2% and 8.22%, respectively.

Next, we test a six-port nonmode selective PL (Phoenix 6PL-0150430). Each input port matches one of the six modes (LP_{01} , LP_{11a} , LP_{11b} , LP_{21a} , LP_{21b} , and LP_{02}). Since the PL has weak mode selectivity, the light from one input port is coupled into all guided modes. However, there is certainly one mode that possesses the most power. The calculated transfer matrix is shown in Table 2. Clearly, R_{ii} is larger than R_{ij} ($i \neq j$), indicating that each mode can only get the largest excitation efficiency from a special corresponding input port. We cannot find two modes getting the largest excitation efficiencies from the same input port. The small values of the nondiagonal parameters indicate the weak mode excitation of other modes. The mode selectivities for the six modes are calculated to be 5.77, 7.66, 2.88, 2.53, 0.50, and 3.06, respectively. Different from the three-mode PL, the output modal field of the six-mode PL is much more complicated and is not easy to identify, as shown in Fig. 4. However, we can recognize the modes by jointly analyzing the captured modal field profile and the calculated transfer matrix. Taking Fig. 4(b) as an example, it looks much like the profile of the LP_{11} mode, and the mode selectivity is not very small. This is in accordance with the calculated results when launching power from port 2, as shown in Table 2. However, we can hardly tell the name of the mode shown in Fig. 4(e), indicating the co-existence of several LP modes. This is confirmed by the two large nondiagonal values for port 5 during the calculation of the corresponding power transfer matrix.

The above experimental results prove the feasibility of the proposed method for characterizing the PL of both mode selective and nonmode selective types. Meanwhile, we also identify two factors affecting the accuracy, including the polarization

Table 2. Calculated Transfer Matrix of a Six-Mode PL

Nonmode Selective	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
Port 1	0.2837	0.0056	0.0212	0.0317	0.0146	0.0020
Port 2	0.0053	0.3656	0.0294	0.0033	0.0088	0.0158
Port 3	0.0018	0.0252	0.3058	0.0139	0.0338	0.0828
Port 4	0.0207	0.0265	0.0433	0.2425	0.0386	0.0063
Port 5	0.0423	0.0219	0.1358	0.0125	0.4109	0.1536
Port 6	0.0000	0.0995	0.0155	0.0635	0.0215	0.4044

Fig. 4. Captured output modal profiles of the six-mode PL. (a)–(f) are for the case of launching power from ports 1–6, respectively.

Fig. 5. Mode selectivity of a three-mode nonmode selective PL.

state of incident light and the perturbation of the FMF. As the concerned modes are the LP modes, the light launched into the input port should be linearly polarized to generate the expected high-order LP mode. Only under such a condition can the output mode field be treated as the superposition of three LP modes. The second factor aims to reduce the mode mixing in the FMF. If the FMF is perturbed, mode coupling occurs between the modes, affecting the accuracy of characterization. The perturbation, such as bending and twisting, is unavoidable when the FMF is very long. Only when the output FMF is short can we guarantee the FMF is with acceptable perturbation. In our experiment, the output FMF is about 50 cm and is kept free from perturbation during the characterization. Then, the FMF is slightly bent and twisted to capture a good LP mode profile without mode coupling between LP mode groups. For the nonmode selective three-mode PL (Phoenix Photonics 3PL-0140106), we test the power transfer matrix when the operation wavelength spreads from 1530 to 1565 nm, across the C-band. The calculated mode selectivity spectral is summarized in Fig. 5. It can be found that the mode selectivity is wavelength dependent. This may come partially from the fact of polarization fluctuation, when the operation wavelength of laser source is tuned.

In conclusion, we propose and experimentally demonstrate a simple method for characterizing the power transfer matrix of PL. By exploiting the optical reflection arising at the output FMF facet, we are able to detect the power of individual

SMF input port and obtain a series of equations based on the theory of energy conservation. From this calculation, the mode-dependent characteristics of the PL can be obtained. The proposed method is verified for both mode selective and nonmode selective PLs.

Funding. National Natural Science Foundation of China (NSFC) (61275069, 61331010), 863 High Technology Plan (2015AA015502), NWO Dutch Photonics Ph.D. Program; ZTE Industry-Academia-Research Cooperation Funds.

REFERENCES

1. P. Sillard, D. Molin, M. Bigot-Astruc, K. de Jongh, and F. Achten, in *Optical Fiber Communication Conference* (Optical Society of America, 2015), paper M2C.2.
2. R. G. H. van Uden, C. M. Okonkwo, V. A. J. M. Sleiffer, H. de Waardt, and A. M. J. Koonen, *Opt. Express* **22**, 119 (2014).
3. Y. Chen, A. Laboto, Y. Jung, H. Chen, C. A. J. M. Sleiffer, M. Kuschnerov, N. K. Fontaine, R. Ryf, D. J. Richardson, B. Lankl, and N. Hanik, *J. Lightwave Technol.* **33**, 1440 (2015).
4. D. J. Richardson, J. M. Fini, and L. E. Nelson, *Nat. Photonics* **7**, 354 (2013).
5. H. Chen, R. van Uden, C. Okonkwo, and T. Koonen, *Opt. Express* **22**, 31582 (2015).
6. N. Bai, E. Ip, Y. K. Huang, E. Mateo, F. Yaman, M. J. Li, S. Bickham, S. Ten, J. Liñares, C. Montero, V. Moreno, X. Prieto, V. Tse, K. M. Chung, A. P. T. Lau, H. Y. Tam, C. Lu, Y. Luo, G. D. Peng, G. Li, and T. Wang, *Opt. Express* **20**, 2668 (2012).
7. J. Carpenter and T. D. Wilkinson, in *Optical Fiber Communication Conference* (Optical Society of America, 2012), paper JW2A.42.
8. I. Giles, A. Obeysekara, C. Rongsheng, D. Giles, F. Poletti, and D. J. Richardson, in *Photonics Society Summer Topical Meeting Series* (IEEE, 2012), p. 212.
9. T. Uematsu, K. Saitoh, N. Hanzawa, T. Sakamoto, T. Matsui, K. Tsujikawa, and M. Koshihara, in *Optical Fiber Communication Conference* (Optical Society of America, 2013), paper OTh1B.5.
10. N. K. Fontaine, in *Photonics Society Summer Topical Meeting Series* (IEEE, 2013), p. 97.
11. R. Ryf, N. K. Fontaine, M. Montoliu, S. Randel, B. Ercan, H. Chen, S. Chandrasekhar, A. Gnauck, S. G. Leon-Saval, J. Bland-Hawthorn, J. R. Salazar-Gil, Y. Sun, and R. Lingle, in *Optical Fiber Communication Conference* (Optical Society of America, 2014), paper W4J.2.
12. R. Ryf, N. K. Fontaine, M. A. Mestre, S. Randel, X. Palou, C. Bolle, A. H. Gnauck, S. Chandrasekhar, X. Liu, B. Guan, R.-J. Essiambre, P. J. Winzer, S. Leon-Saval, J. Bland-Hawthorn, R. Delbue, P. Pupalais, A. Sureka, Y. Sun, L. Grüner-Nielsen, R. V. Jensen, and R. Lingle, in *Frontiers in Optics* (Optical Society of America, 2012), paper FW6C.4.
13. R. Ryf, S. Randel, N. K. Fontaine, M. Montoliu, E. Burrows, S. Chandrasekhar, A. H. Gnauck, C. Xie, R.-J. Essiambre, P. Winzer, R. Delbue, P. Pupalais, A. Sureka, Y. Sun, L. Gruner-Nielsen, R. V. Jensen, and R. Lingle, in *Optical Fiber Communication Conference* (Optical Society of America, 2013), paper PDP5A.1.
14. S. G. Leon-Saval, A. Argyros, and J. Bland-Hawthorn, in *Frontiers in Optics* (Optical Society of America, 2010), paper FWA.4.
15. S. G. Leon-Saval, N. K. Fontaine, J. R. Salazar-Gil, B. Ercan, R. Ryf, and J. Bland-Hawthorn, *Opt. Express* **22**, 1036 (2014).
16. A. M. Velazquez-Benitez, J. C. Alvarado, G. Lopez-Galmiche, J. E. Antonio-Lopez, J. Hernandez-Cordero, J. Sanchez-Mondragon, P. Sillard, C. M. Okonkwo, and R. Amezcua-Correa, *Opt. Lett.* **40**, 1663 (2015).
17. B. Huang, N. K. Fontaine, R. Ryf, B. Guan, S. G. Leon-Saval, R. Shubochkin, Y. Sun, R. Lingle, and G. Li, *Opt. Express* **23**, 224 (2015).
18. N. K. Fontaine and R. Ryf, in *Optoelectronics and Communications Conference and Photonics in Switching* (Optical Society of America, 2013), paper MR2_2.