Fiber-optic device for mode division

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Abstract. In this paper, we describe a simple device for mode division based on fused quartz fiber-optic coupler. An equivalent circuit of a photonic lantern for such a device is considered. The experimental test data of the device samples are presented. As test samples showed, this technology allows to obtain satisfactory parameters for simple and inexpensive devices with one multimode port and 2-5 single-mode ports.

1. Introduction
At the current stage of the development of infocommunication technologies, standard single-mode optical fibers, which nowadays are used on transport telecommunication networks, have practically exhausted their resource of increasing the capacity. Fiber-optical transmission lines with single-mode optical fibers approach the so-called "nonlinear Shannon limit" [1-4]. The main factors in the distortion of signals in optical channels are the factors of nonlinearity. The main factors of nonlinearity increase are due to small diameter of the core of standard single-mode optical fibers, the increase in the power introduced into the optical fiber, the increase of the number of optical channels of spectral multiplexing and the increase a length of transmission lines of transport networks. This factors are actioned at the physical level and it's are almost impossible to reduce in standard singlemode optical fibers. As an alternative, there are considered a systems of spatial multiplexing [5 - 10] with multicore, fewmode or even multimode optical fibers in the fewmode transmission mode. The practical using of such systems on transport networks are predicted by the analysts by 2025 [8]. When using fewmode or multimode optical fibers the mode division multiplexers / demultiplexers are required to ensure the separation of the modes in lightguide. Mode multiplexing is known for a long time [11]. From the point of view of modes division, devices based on diffractive optical elements (DOE) demonstrate good results [5, 7, 12-14]. The main problem limiting the use of DOE in fiber optics is related to the difficulty of integrating them into fiber devices for implementing the "in-fiber" technology. The same drawback is typical for devices on macro-optics elements. To date, most widely used the mode division multiplexers, built on the principle of "Chinese lantern" [5-10, 17-25]. Devices implementing this principle are called "photonic lantern" [17]. At such multiplexers, a singlemode optical fiber bundle is drawn into a one fiber matching with a multimode optical fiber. The photonic lantern types
are known, having 3-7, 19 and even up to 61 singlemode ports [5,7,18,20]. Also, relatively simple mode multiplexers based on fiber optic couplers manufacturing technology are known [26-32]. In the photonic lantern, in the first approximation, the end of the multimode optical fiber is joined to the ends of the bundle of several singlemode optical fibers that have been tapped into the common structure. In the mode selective couplers a multimode and a singlemode optical fibers are fused together at the side surfaces of fibers in some area at a certain distance between the axes of the lightguides. It has been suggested that, under certain conditions, the mode division in the photonic lantern and the mode selective coupler will be equivalent. In this paper we present the results of an experimental verification of this assumption.

2. Brief description of a photonic lantern

The term photonic lantern was first introduced assumedly in [17]. There was well-known the conditional diagram of a photonic lantern (Fig. 1), explaining its design and the principle of operation. Here MMF core is the core of multimode optical fiber. And SMF core is the core single-mode optical fibers. As follows from Fig. 1, the bundle of singlemode optical fibers is tapered into a common fiber structure matched to the multimode optical fiber. During drawing the singlemode fiber stappering on the cone. As already noted, in the first approximation, the ends of tapered singlemode optical fibers are joined to the end of a multimode optical fiber.

![Figure 1. Scheme of the photonic lantern [17].](image)

3. Manufacture of fused fiber-optic couplers

The technology of production of fused fiber-optic couplers is well known and debugged. In our work for the manufacture of a multiplexer based on fused fiber-optic couplers the workstation Lightel CW-5000 was used, which enables conduct different types of specific fiber processing and provide an opportunity manufacturing a wide range of fiber optic products, including couplers, splitters, fiber cones, and the like. Flexible structure and intellectual automatic control makes this workstation an effective tool for production of fiber-related products and research. Station is a welding machine consisting of three main parts: hydrogen burners, movable vacuum heads and control panels. A workstation can controlled or from a computer, which makes it possible to step by step the performance of the product or from the control panel, which is used to define the functions with which you can perform work in standard settings. The main parameters of technological process include span length, temperature and welding time. To determine the percent of fibers overlapping it is used a built-in tester that automatically displays the power ratio in the coupler ports on the computer display. Using this workstation, the X-type fused fiber-optic couplers was made from a standard multimode silica glass optical fiber with a core diameter of 50 μm and from a standard singlemode optical fiber (SMF-28e type). Schematic representation of the made mode division multiplexer based on the X-type fiber-optic coupler is shown in Fig. 2.

![Schematic representation of the made mode division multiplexer.](image)
4. Experiment description
In order to test the hypothesis put forward, a mode division multiplexer based on an X-type fiber-optic coupler was manufactured. During it was made, the overlap of the optical fibers was not specifically installed. The tests were carried out according to the scheme shown in Fig. 3.

For the measurements, we used the device of R2D2. It including a generator of probing optical pulses of a Gaussian shape with a duration of 580 ps and a stroboscopic oscilloscope with a photodetector. The optical pulses from the R2D2 output through a short patchcord of a standard singlemode optical fiber SMF28e of about 2.0 m in length were introduced into a standard multimode optical fiber with a core diameter of 50 μm. The input was performed with an axial mismatch of 10.0 μm, which ensured a uniform excitation of the guided modes in the multimode fiber [33]. The length of the fiber was 223 m. The output of the multimode optical fiber was connected to the input multimode port of the manufactured mode division multiplexer. A short patchcord of the standard singlemode optical fiber SMF28e with a length of about 2.0 m was connected to the input of the photodetector of R2D2.

At first, the second end of the single-mode optical fiber after the necessary processing with the alignment device of the fusion splicer Ericsson FSU-975 were coaxially aligned with the optical fiber of the output singlemode port of the manufactured mode division multiplexer. Then the impulse response was measured by using a R2D2, at the single-mode output of the multiplexer and the result of the measurements was memorized.

In a next step, the second end of the singlemode optical fiber was connected to the multimode optical fiber of the output multimode port of manufactured mode division multiplexer. It was by means of the alignment device of the fusion splicer Ericsson FSU-975. Then it was scanned the end of the multimode optical fiber at the output of the multiplexer by the single-mode optical fiber with a certain step. At the same time, at each step of the scan, a pulse response was measured and memorized at the multimode output of the multiplexer and memorized the thermal photograph from the fusion splicer. These thermal photographs reflects the relative position of the optical fibers in the alignment step. The result of measuring the typical impulse response at one of the scanning steps is shown in Fig. 4, and the example of the thermal photograph in Fig. 5.
Upon completion of the scan, the impulse responses measured at the output of the multimode port of the multiplexer were compared with the impulse response at the output of the single-mode port. As a comparison criterion, the correlation coefficient was chosen. The value of the axial misalignment at each step was estimated from thermal photography. Obtained as a result of processing the measurement data the dependence of the correlation coefficient on the axial misalignment of the singlemode fiber at the input of the photodetector of the measuring instrument relative to the multimode fiber of the port of the mode division multiplexer is shown in Fig. 6.

5. Analysis of test results of your paper

In analyzing the test results, we was following from some provisions.

Taking into account the design of the photonic lantern, we believe that when the modes is uniformly excited at the input of a multimode optical fiber, the response at the output of the multimode fiber at a certain value of the axial misalignment is equivalent to the response at the corresponding singlemode port of the photonic lantern.

The form of response to the Gaussian sounding pulse allows us to conclude that there is a significant manifestation of the differential mode delay. From this, we believe that the impulse response on the output of a single-mode optical fiber scanning the end of the multimode optic fiber of the multiplexer port is dependent on the modes composition and the ratio of the power levels of individual modes.

This allows one estimating the degree of correspondence of a single-mode multiplexer port based on a fiber-optic coupler to the port of a multiplexer, such as a photonic lantern, according to the degree of coincidence of the pulse responses. Namely, we comparison the pulse response at the singlemode output port of the multiplexer and the pulse response at the output of singlemode fiber at the end of multimode fiber with some axial mismatch.

The analysis of the dependence shown in Figure 6 shows for most values of the axial misalignment from -20 μm to +20 μm, the correlation coefficient of the compared impulse responses lies in the range from 0.5 to 0.7.

However, for an axial mismatch of 15.25 μm, the correlation coefficient is 0.97.

This allows us to conclude that with the appropriate selection of technology parameters on individual ports of multiplexers made using the photonic lantern technology and the fused fiber-optic coupler technology, it is possible to obtain signals close under the modes composition with same the ratio between the levels of individual modes. In other words, the experiment confirms the validity of the proposed assumption that under certain conditions, the mode division in optical multiplexers made using the photonic lantern technology and the fused fiber-optic coupler technology will be equivalent.
6. Conclusion
It has been experimentally confirmed that with the appropriate choice of the parameters of the mode division multiplexer based on the fused fiber-optic coupler technology, it is possible to obtain the same mode division as in the photonic lantern. This allows to believe that this technology allows to obtain a simple and inexpensive device with one multimode port and 2-5 single-mode ports with completely satisfactory parameters.

7. References
[1] Mitra P P and Stark J B 2001 Nature 411 1027
[2] Essiambre R-J, Kramer G, Winzer P J, Foschini G J and Goebel B 2010 Journal of Lightwave Technology 28(4) 662
[3] Mecozzi A, Essiambre R-J 2012 Journal of Lightwave Technology 30(12) 2011
[4] Ellis A D 2012 Proc. of SPIE 8434 84340H
[5] Richardson D J, Fini J M and Nelson L E 2013 Nature Photonics 7 354
[6] Amaya N, Yan S, Channegowda M, Rofofee B R, Shu Y, Rashidi M, Ou Y, Hugues-Salas E, Zervas G, Nejahati R, Simeonidou D, Puttnam B J, Klaus W, Sakaguchi J, Miyazawa T, Awaji Y, Harai H and Wada N 2014 Optics Express 22(33) 638
[7] Amphawan A 2011 Optical Engineering 50(10) 102001-102011
[8] Kuschnerov M and Stieffer V 2013 ECOC (Access mode: http://modegap.eu/wp-content/uploads/2013/10/Coriant-Kuschnerov-ECOC-Market-Focus-20131.pdf) (25.09.2013).
[9] Li G, Bai N, Zhao N and Xial C 2014 Advances in Optics and Photonics 6 413
[10] Klaus W, Puttnam B J, Luis R S, Sakaguchi J, Delgado Mendinueta J-M, Awaji Y and Wada N 2017 Opt. Commun. Netw. 9(4) 1
[11] Berdague S and Facq P 1982 Applied Optics 21(11) 1950
[12] Pavelev V S, Soifer V A, Duparre M, Kowarschik R, Luedeke B, Kley B and Karpeyev S V 1998 Computer Optics 18 115
[13] Karpeyev S V, Pavlev V S, Duparre M, Luedeke B, Roksiutk K and Shroter Z 2002 Computer Optics 23 4
[14] Khonina S N 2002 Computer Optics 23 15
[15] Kadomina E A, Bezus E A, Doskolovich L L 2017 Generation of high-frequency interference patterns of evanescent electromagnetic waves at Fabry-Perot resonances in dielectric photonic crystals Computer Optics 41(3) 322-329 DOI: 10.18287/2412-6179-2017-41-3-322-329
[16] Gavrilov A V, Pavlev V S 2017 Integrated fiber-based transverse mode converter Computer Optics 41(4) 510-514 DOI: 10.18287/2412-6179-2017-41-4-510-514
[17] Leon-Saval S G, Birks T A, Bland-Hawthorn J and Englund M 2005 Optics Letters 30(19) 2545
[18] Noordegraaf D, Skovgaard P M W, Maack M D, Bland-Hawthorn J, Haynes R and Lægsgaard J
2010 Optics Express 18(5) 4673

[19] Leon-Saval S G, Argyros A and Bland-Hawthorn J 2010 Optics Express 18(8) 8430
[20] Noordegraaf D, Skovgaard P M W, Sandberg R H, Maack M D, Bland-Hawthorn J, Lawrence J S and Læsgaard J 2012 Opt. Lett. 37 452
[21] Birks T A, Mangan B J, Diez A, Cruz J L and Murphy D F 2012 Optics Express 20(13) 13996
[22] Fontaine N K, Ryf R, Bland-Hawthorn J and Leon-Saval S G 2012 Optics Express 20(24) 27123
[23] Leon-Saval S G, Fontaine N K, Salazar-Gil J R, Ercan B, Ryf R and Bland-Hawthorn J 2014 Optics Express 22(1) 1
[24] Birks T A, Gris-Sánchez I, Yerolatsitis S, Leon-Saval S G and Thomson R R 2015 Advances in Optics and Photonics 7 107
[25] Ryf R, Fontaine N K, Chen H, Guan B, Huang B, Esmaeelpour M, Gnauck A H, Randel S, Yoo S J B, Koonen A M J, Shubochkin R, Sun Y and, Lingle R 2015 Optics Express 23(1) 235
[26] Shin W, Choi S and Oh K 2002 Optics Letters 27(21) 1884
[27] Love J D and Riesen N 2012 Optics Letters 37(19) 3990
[28] Jung Y, Chen R, Ismaeel R, Brambilla G, Alam S-U, Giles I P and Richardson D J 2013 Optics Express 21(20) 24326
[29] Rand I, Ismaeel R, Lee T, Oduro B, Jung Y and Brambilla G 2014 Optics Express 22(10) 11610-11619
[30] Chang S H, Chung H S, Ryf R, Fontaine N K, Han Ch, Kyung J P, Kim K, Lee J Ch, Lee J H, Kim B Y and Kim Y K 2015 Optics Express 23(6) 7164
[31] Kyung J P, Kwang Y S, Young K K, Lee J H and Kim B Y 2016 Optics Express 24(4) 3543
[32] Chang S H, Moon S-R, Haoshuo Ch, Ryf R, Fontaine N K, Kyung J P, Kwangjoon K and Joon K L 2017 Optics Express 25(5) 5734
[33] Andreev V A and Bourdine A V 2004 Multimode optical fibers. Theory and applications on high bit rate communication networks (Moscow: Radio and svyaz) 248 p

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