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(71) Applicant(s)
Polskie Centrum Fotoniki I #wiat#owodów

(72) Inventor(s)
Szostkiewicz, #ukasz;Kukli#ska, Ma#gorzata;Napiera#a, Marek;Nasi#owski, Tomasz;Ostrowski, #ukasz;Pytel, Anna;Szyma#ski, Micha#;Wysoki#ski, Karol;M#kowska, Anna;Murawski, Micha#;Tenderenda, Tadeusz;Bie#kowska, Beata

(74) Agent / Attorney
Golja Haines & Friend, PO Box 1014, South Perth, WA, 6951, AU

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(71) Applicant: **POLSKIE CENTRUM FOTONIKI I ŚWIATŁOWODÓW** [PL/PL]; Rogoznica, 312, 36-060 Głogów Małopolski (PL).

(72) Inventors: **SZOSTKIEWICZ, Łukasz**; ul. Wąska, 8a/10, 97-100 Toruń (PL). **KUKLIŃSKA, Małgorzata**; Pawłowa, 61, 20-455 Lublin (PL). **NAPIERAŁA, Marek**; ul. Lazurowa, 185A/55, Warszawa 01-476 (PL). **NASIŁOWSKI, Tomasz**; ul. Dzika, 15/12, 00-172 Warszawa (PL). **OSTROWSKI, Łukasz**; ul. Jana Kazimierza, 228, 05-126 Nieporęt (PL). **PYTEL, Anna**; ul. Sotta Sokoła Kazimierza, 1A/20 , 02-790 Warszawa (PL). **SZYMAŃSKI, Michał**; ul. Hery, 25C/25, 01-497 Warszawa (PL). **WYSOKIŃSKI, Karol**; ul. Piołunowa, 43, 81-589 Gdynia (PL). **MĄKOWSKA, Anna**; Ołowiana, 7, 25-752 Kielce (PL). **MURAWSKI, Michał**; ul. Szwankowskiego, 4/19, 01-318 Warszawa (PL). **TENDERENDA, Tadeusz**; Migdałowa, 69, 02-796 Warszawa (PL). **BIEŃKOWSKA, Beata**; Modzelewskiego, 26/603, 02-679 Warszawa (PL).

(74) Agent: **RUMPEL, Alicja**; ul Częstochowska, 1a, 93-115 Łódź (PL).

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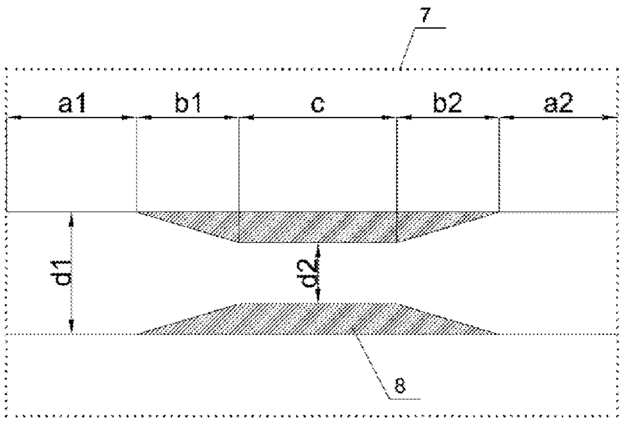

Fig. 3

(57) Abstract: A device for selective increasing higher-order modes' losses (3), characterized in that it comprises an optical fiber taper executed on a multi-mode fiber multi-mode at a certain wavelength, and that the fiber taper(7) has separated regions, i.e. non-tapered fiber regions of (a1) and (a2) in total lengths, in which fiber diameter equals (d1), transition regions of (b1) and (b2) in total lengths, in which fiber diameter is reduced/increased, respectively; and a taper waist region of (c) in total length, in which fiber diameter equals (d2), and the taper level is defined as R=((d1-d2)/d1)·100% and equals at least 20%, and the length of the transition regions is (b1), at least 0.5 mm, (b2) is equal or larger than 0 mm, the length of the taper waist is at least 0.5 mm, and the taper area is coated with a filtering substance with attenuating properties.

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Device for selective increasing higher-order modes' losses

The object of the invention is a device for selective increasing higher-order modes' losses, particularly in gradient multi-mode fibers (MMF). The device can be used, in particular, to increase the throughput of multi-mode transmission systems by minimizing the negative effect of intermodal dispersion, to ensure single-mode operation in optical fiber lasers, or to improve beam quality in multi-mode optical fibers by ensuring single- or few-mode operation in multi-mode optical fibers. After applying the device, one or few first mode groups are left in a multi-mode optical fiber.

Increasing the throughput is one of the primary challenges for new-generation communication systems based on optical fibers. This is related to continually growing demand for growing volumes of data, as well as increased telecommunication network traffic. The phenomenon concerns traffic in both public networks and in information processing and storage centers. Due to relatively short distances, data centers usually apply multi-mode fibers, where throughput is mainly limited by intermodal dispersion. Networks of this type are often based on VCSEL lasers and MMF fibers, where the primary limitation is the effect of intermodal dispersion, *id est* the difference in group velocity, and thus in the propagation time for various modes. The negative effect of intermodal dispersion is expressed in impulse widening within a time domain, which results in limiting the signal throughput or transmission range.

Ensuring single-mode operation is also a challenge in terms of optical fiber laser structure. Single-mode lasers offer improved beam quality and, in some applications, it is necessary to ensure the single-mode operation of lasers. One of possible solutions to this problem can be to insert a device for filtering out higher-order modes in the laser resonator to allow for the use of multi-mode fiber of large core diameter as an active medium, in which only one mode will be effectively propagated. Ensuring single- or few-mode operation in a multi-mode fiber has positive effect on beam quality, as it reduces the discrepancy in beam diffraction and outlet and allows the beam to be focused in a smaller area, to produce increased laser precision.

One of the ways to eliminate the adverse effects related to applying multi-mode fibers is to apply single-mode fibers (SMF) instead of multi-mode ones. However,

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networks based on single-mode fibers are much more expensive to manufacture and install, and thus less eagerly applied in data centers. The use of single-mode fibers as active media in lasers also has its limitations, resulting from non-linear effects occurring with small mode fields. A device for selective increasing higher-order modes' losses according to the invention is much shorter than a complete resonator, and therefore the non-linear effects resulting from limiting the mode field will occur at very small distances only.

Literature includes numerous works on active systems for selecting and limiting the number of modes. For instance, a solution that limits the number of propagating modes and applying complex and costly external systems (optical filtering matrices) was published in an article by G. Stępniak, L. Maksymiuk and J. Siuzdak, titled "Binary phase spatial light filters for mode selective excitation of multimode fibers", published in the Journal of Lightwave Technology 29/13 (2011). Other known methods to reduce the number of modes require precise optical systems, used to stimulate select modes only. These were published, among others, in an article by L. Jeunhomme and J.P. Pocholle, titled "Selective mode excitation of graded index optical fibers", published in Applied Optics 17/3 (1978). Due to their complex structures and high costs, the presented systems can be executed in laboratory conditions only.

Other mode filtration methods are familiar, in which the structure of the optical fiber is modified. An example is a solution according to JP2001133647, which proposed a planar structure, where periodical changes of the lateral surface of the core cladding are used to disperse the higher-order modes leaving the core. Such a modified waveguide section can be included in the structure of a traditional optical fiber network. In addition, such an element does not require power supply.

In turn, patent description ref. US2003169965 presents a method of filtering out higher-order modes through consisting in including into the optical fiber systems bended fibers with small-radius curvature to selectively increase higher-order modes' losses. The use of small-radius curvature eliminates higher-order modes, and, as stated in the invention, transmission is more effective and faster.

Another method of modifying waveguide structure is to interfere with its chemical composition, in order to change the light propagation conditions inside the optical fiber. Such a description is included in patent ref. US2014286606, in which doped and non-doped regions are placed alternately. In result, higher-order modes is scattered and attenuated.

A solution according to patent ref. US7194156 presents a counterpart of an optical communication system, used to filter out higher-order modes. The invention can be used to increase the throughput of communication systems based on multi-mode optical fibers. An element used for filtering out higher-order modes can be executed twofold. In one of the methods, the tip of the multi-mode fiber is tapered, and the signal is led through a lens to a detector. An element constructed this way can filter out higher-order modes in a manner that only a certain group of modes remains, where every mode reaching the detector can be treated as a separate signal. In this embodiment, signal is coupled with the use of bulk optics, which results in increasing the size of the device and additional losses. Furthermore, this invention does not assume the taper coating with a filtering substance.

In turn, patent description ref. WO2015138492 presents a structure for conducting quasi-multi-mode communication on multi-mode fibers. In this solution, a light signal from at least two lasers is processed by an optoelectronic TOSA system and entered to a single-mode fiber in the form of a quasi-multi mode signal, and then, after propagating through the transmission path, it is received by an analogue ROSA device. The ROSA receiver blocks at least one higher-order mode signal.

Application document ref. US 20070081768 describes an optical communication system based on multi-mode fibers, and a method to increase the throughput of this system. A part of this system is an element used to filter out higher-order modes, based on a narrowing. A multi-mode optical fiber is tapered in a manner that the basic mode only is propagated in its narrowest part. A configuration for power inlet or outlet to and from a single-mode optical fiber is also presented. The patent describes a method of executing the tapering in the planar method. At the same time, the patent does not assume covering a taper by means of a filtering substance.

Patent ref. US 7184623 B2 also presents an invention which can be used to increase the throughput of telecommunication systems based on multi-mode optical fibers. In this case, an adiabatic coupler, possibly a tapered optical fiber, was applied to filter out higher-order modes. According to the solution, in the taper region higher-order modes leak out of the core and are absorbed by the cladding or emitted out of the cladding. The solution does not assume placing a filtering substance on a taper region.

Works published in an article by Y. Jung, G. Brambilla and D.J. Richardson, titled “Broadband single-mode operation of standard optical fibers by using a sub-wavelength optical wire filter”, published in the Optics Express 16/19 (2008), present a method of filtering out higher-order modes by applying a fiber taper. The key is to adapt the geometry, particularly in the transition regions. In the proposed solution, the transition regions are adiabatic for the first-order mode and simultaneously non-adiabatic – for higher-order modes. Such a taper geometry introduces large losses for higher-order modes. In the presented solution, in order to ensure that propagation was allowed for fundamental mode only, the taper had to be executed in a 100-times smaller diameter to this of the core. In addition, the taper is not coated with a substance, which significantly reduces the effectiveness of filtering higher-order modes. Due to the absence of a filtering substance in the taper region the filtered modes are led on the glass-air threshold. A large taper level is required to introduce significant losses for high-order modes. At the same time, the application of a filtering substance significantly increase filtered modes’ losses, which allows the taper to be shorter and the taper level to be smaller. In result, improved effectiveness is obtained, compared to an embodiment without the filtering substance.

Coating the optical fiber taper region is used in evanescent field sensors. An exemplary evanescent field sensor is presented in patent ref. US 6103535 A, which describes the structure of a sensor based on an optical fiber taper coated with fluorophore-reacting material. Fluorescence takes place when the material coating the tapering reacts with the fluorophores in the presence of evanescent field in the tapered optical fiber. The key element of this invention is the material used to coat the tapering. In contact with a specific substance, this material undergoes a chemical reaction, which

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causes fluorescence. This type of sensors applies multi-mode optical fibers, which guarantee higher sensor sensitivity.

Coating the optical fiber taper region can also be used in the structure of impulse mode-locked fiber lasers. In their publication titled “A practical topological insulator saturable absorber for mode-locked fiber laser” and published in Nature 5/8690 (2015), P. Yan, R. Lin, Sh. Ruan, A. Liu, H. Chen, Y. Zheng, S. Chen, C. Guo and J. Hu presented a tapered, single-mode optical fiber SMF-28 with a saturable absorbent, which is characterized by its transparency at certain wavelengths while the signal intensity is high enough.

Patent ref. US 8384991 presents an invention consisting of a saturable absorbent which could be applied, among others, in the structures of impulse fiber lasers. The subject of the invention is a special substance, a mixture of carbon nanotubes and polymer composites. A fragment of the tapered optical fiber, coated with this substance, is used in the structure of the impulse fiber laser.

Patent ref. US 6301408 presents an invention consisting of a fiber Bragg grating inscribed in the optical fiber taper region, where the taper region is coated with a special polymer. By adapting a suitable refraction index in the taper’s polymer coating, it is possible to control the Bragg wavelength. The invention according to the proposed structure can be used to build an add/drop multiplexer. In the presented solution, the properties of the fundamental mode is changed.

The purpose of the invention was to develop a device for selective increasing higher-order modes’ losses using an optical fiber element to contribute to increasing the throughput of multi-mode transmission systems or to enable single-mode operation in fiber lasers. Its primary functionalities include: ensuring selective increase in higher-order modes’ losses, passivity, small time delay, low insertion and reflection losses for selected modes, and compatibility with standard multi-mode transmission systems.

Furthermore, since the device is all-fiber, it is passive hence does not require any power supply. The device is used to reduce the negative effect of intermodal dispersion in multi-mode transmission systems of limited throughput or in those requiring complex multiple-input, multiple-output (MIMO) algorithms. In addition, due to its small length (few up to dozen centimeters), the device does not introduce an additional time delay in the signal. In optical fiber transmission, where data transfer speed is the primary advantage, this is a key functionality.

In accordance with the invention there is provided a device for selective increasing higher-order modes's losses suitable for selectively increasing higher-order modes' losses in transmission systems to increase the throughput and ranges of transmission systems based on VCSEL light sources at a wavelength of 850nm, said device being in a form of an at least one optical fiber taper executed on a multi-mode fiber (at a specific wavelength). The optical fiber taper has separated regions, i.e. non-tapered optical fiber regions of (a1 and a2) in total lengths, in which the fiber diameter equals (d1) (the length of these regions do not affect the operation of the device); located between said non-tapered optical fiber regions, transition regions of (b1) and (b2), respectively, in total lengths in which the fiber diameter is decreasing/increasing respectively; and located between said transition regions, a taper waist region of (c) in total length, in which the optical fiber diameter equals (d2). The taper level is defined as $R=((d1-d2)/d1)\cdot 100\%$ and is preferably contained in a 20-97% range, and the length of transition region (b1) is preferably from 0.5 mm to 75 mm, and the length of transition region (b2) is preferably from 0 mm to 75 mm, and the length of the taper waist region (c) is preferably from 0.5 mm to 75 mm. The optical fibre is composed of a core and a cladding which at the position of the transition regions (b1) and (b2) and the taper waist region is coated with a filtering substance with attenuating properties and with a higher refractive index than that of the optical fibre cladding material, and the fibre is multi-mode at 850nm. Whereas, in a beneficial embodiment of the invention, the filtering substance is applied on at least one fragment of the optical fiber taper.

In a beneficial embodiment of the invention, the filtering substance has attenuating properties – absorptive and/or scattering properties (on a given, utilized wavelength) and/or has a higher light refraction index than the said optical fiber cladding material. The filtering substance, which constitutes an integral part of the device, is selected from among: paraffin, vaseline or similar hydrocarbons, fatty acids, their salts or esters, graphite, graphene, soot, other forms of carbon and their derivatives, polymers dissolved in such organic solvents as polystyrene, ethyl cellulose, nitrocellulose, cellulose acetate, methyl cellulose, polyvinyl acetate, methyl methacrylate and their derivatives, polymers with low softening temperatures, such as polyvinyl chloride, ethylene-vinyl acetate, acrylic, octane-cellulose, butyl-cellulose polymers, polyimides, polyamides, polyolefins, perfluored polymers, R-Si-O organosols, polydimethylsiloxanes, polybutadiene rubber, ultraviolet-hardened polymers, epoxy resins, epoxy-acrylic resins, urethane-acrylic resins, silicone-epoxy resins, silicone-acrylic resins, epoxy-acrylic resins, organic fluids, such as: glycerin, toluene, styrene, carbon tetrachloride, carbon disulfide, silicone oil, concentrated carbohydrate solutions, immersive oil, metallic layers, metal oxides or mixtures containing at least one of the aforementioned substances or their derivatives.

In a beneficial embodiment of the invention, a serial connection of the device into an optical fiber line is preferably executed through splicing or connectors. In another beneficial embodiment of the device, the taper can be executed directly on the optical fiber forming the optical fiber line. In another beneficial embodiment of the device, it can be also included in the detector (receiver).

Whereas, in a beneficial embodiment of the invention, a taper executed on an optical fiber according to the OM2 or OM3 standard has the following dimensions: b1 = b2 = 10 mm, c = 10 mm, d1 = 125 μm, d2 = 25 μm (R=80%), and the connection of the device with the optical fiber line is executed in the form of a splice between a fiber and the optical fiber taper, whereas the multi-mode optical fiber used is executed according to the OM2 or OM3 standard. In a beneficial embodiment of the invention, the taper region is coated with a filtering substance which is an absorbent which, in this beneficial embodiment, is colloidal graphite.

In another beneficial embodiment of the invention, a taper executed on an optical fiber according to the OM4 standard has the following dimensions: b1 = 5 mm, b2 = 0 mm, c = 10 mm, d1 = 125 μm, d2 = 20 μm (R=84%), and the connection of the device with the optical fiber line is executed in the form of a fiber connector between a fiber and the optical fiber taper, whereas the multi-mode optical fiber used is executed according to the OM4 standard. In a beneficial embodiment of the invention, the taper region is coated with a filtering substance consisting in an absorbent which, in this beneficial embodiment, is paraffin.

In another beneficial embodiment of the invention, a taper executed on a multi-mode step-index optical fiber, numerical aperture of 0.37 (defined as a square root of the difference of the core's refractive index, squared, and the casing's refractive index, squared), of 100 µm in core diameter and 300 µm in casing diameter, has the following dimensions: b1 = 30 mm, b2 = 20 mm, c = 20 mm, d1 = 300 µm, d2 = 9 µm (R=97%), and is coated with a filtering substance covering the taper region. In a beneficial embodiment of the invention, the filtering substance has a higher refractive index than the optical fiber cladding material which, in this beneficial embodiment, consists in carbon disulfide.

Whereas, the device for selective increasing higher-order modes' losses is serially connected to the multi-mode fiber's structure, between at least one transmitter and at least one detector (receiver), preferably close to the detector, or, in another embodiment, the device is an element of an optical line as part of a fiber laser's resonator cavity.

In a beneficial embodiment, a specific device configuration is set with at least one VCSEL light source at 850 nm and OM3 or OM4 fibers.

The invention was presented in detail in examples and figures, which, however, do not exhaust the possible configurations of the invention, as resulting from its operation principle.

Fig. 1 presents a diagram of a transmission system utilizing OM2 or OM3 fibers (2), to which signal is entered by a transmitter (1), and a device for selective increasing higher-order mode losses (3) is incorporated in the fiber line (2), before the receiver (4).

Fig. 2 presents a close-up of the device (3), with visible splices (5), used to connect the device in the fiber line, and the OM2 or OM3 fiber (2), on which an optical fiber taper (7) is executed.

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Fig. 3 presents a diagram of the optical fiber taper (7) with marked regions: of the non-tapered fiber of (a1) and (a2) in total lengths and of (d1) in total diameter, of transitional regions of (b1) and (b2) in total lengths, and of the taper waist region of (c) in total length and (d2) in total diameter, where the taper region is coated with an absorber (8). Dimensions are out of scale.

Fig. 4 presents a diagram of a transmission system utilizing an OM4 fiber (6), to which signal is coupled from a transmitter (1), and a device for selective increasing higher-order modes' losses (3) is incorporated in the fiber line (6), before the receiver (4).

Fig. 5 presents a close-up on the device (3), with a visible connector (9) for connecting the device in the optical fiber line, and the OM4 fiber (6), on which an optical fiber taper (7) is executed.

Fig. 6 presents a diagram of the optical fiber taper with marked regions: of a non-tapered optical fiber of (a1) in total length and (d1) in total diameter, of a transition region of decreasing diameter (d1) and of a taper waist region of (c) in total length and (d2) in total diameter, where the taper region is coated with an absorber (8). Dimensions are out of scale.

Example 1

A device for selective increasing higher-order modes' (3) comprises an optical fiber taper executed on a multi-mode fiber (in the OM2 or OM3 standard) and serially inserted between a transmitter (1) and a receiver (4). The optical fiber taper (7) as separated regions, i.e. non-tapered fiber regions of (a1) and (a2) in total lengths, in which fiber diameter equals (d1) – the lengths of these regions do not directly affect the operation of the device; a transition regions of (b1) and (b2) in total lengths, in which fiber diameter is reduced/increased, respectively; and a proper taper area of (c) in total length, in which fiber diameter equals (d2). The device is connected into an optical fiber line by means of connections (5) executed as fiber splices (2).

Taper level is defined as $R=((d1-d2)/d1)\cdot 100\%$.

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In this device example, b1 = b2 = 10 mm, c = 10 mm, d1 = 125 µm, d2 = 25 µm (R=80%).

The taper is coated with a filtering substance (8), an absorbent, which, in this beneficial embodiment, is colloidal graphite.

The device for selective increasing higher-order modes' losses is used in transmission systems to increase the throughput and ranges of transmission systems based on VCSEL light sources at a wavelength of 850 nm and OM2 or OM3 fibers.

Example 2

A device for selective increasing higher-order modes' losses (3) comprises an optical fiber taper executed on a multi-mode fiber (in the OM4 standard) and serially inserted between a transmitter (1) and a receiver (4). The optical fiber taper (7) has separated regions, i.e. non-tapered fiber regions of (a1) in total length, in which fiber diameter equals (d1) – the length of this region does not directly affect the operation of the device; a transition zone area of (b1) in total length, in which fiber diameter (2) is reduced; and a taper waist region of (c) in total length, in which fiber diameter equals (d2). The device is incorporated in an optical fiber line by means of a connection (5), and is directly connected to a receiver (detector).

Taper level is defined as $R=((d1-d2)/d1)\cdot 100\%$.

In this device example, b1 = 5 mm, b2 = 0, c = 10 mm, d1 = 125 µm, d2 = 20µm (R=84%).

The taper is coated with a filtering substance (8), an absorbent, which, in this beneficial embodiment, is paraffin.

The device for selective increasing higher-order modes' losses is used in transmission systems to increase the throughput and ranges of transmission systems based on VCSEL light sources at a wavelength of 850 nm and OM4 fibers.

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Example 3

A device for selective increasing higher-order modes’ (3) comprises an optical fiber taper executed on a multi-mode step-index fiber at a wavelength below 1100 nm, numeric aperture 0.37 (defined as a square root of the difference of the core’s refractive index, squared, and the cladding’s refractive index, squared), of 100 µm in core diameter and 300 µm in casing diameter. The optical fiber taper is serially inserted a fiber laser’s resonator. The optical fiber taper (7) as separated regions, i.e. non-tapered fiber regions of (a1) and (a2) in total lengths, in which fiber diameter equals (d1) – the lengths of these regions do not directly affect the operation of the device; a transition regions of (b1) and (b2) in total lengths, in which fiber diameter is reduced/increased, respectively; and a taper waist region of (c) in total length, in which fiber diameter equals (d2). The device is incorporated in an optical fiber line by means of spliced connections.

Taper level is defined as $R=((d1-d2)/d1)\cdot 100\%$.

In this device example, b1 = 30 mm b2 = 20 mm, c = 20 mm, d1 = 300 µm, d2 = 9 µm (R=97%).

The taper is coated with a filtering substance (8) with a higher refractive index than the optical fiber cladding material, and which, in this beneficial embodiment, is carbon disulfide.

Reference numbers and letters appearing between parentheses in the claims, identifying features described in the embodiment(s) and/or example(s) and/or illustrated in the accompanying drawings, are provided as an aid to the reader as an exemplification of the matter claimed. The inclusion of such reference numbers and letters is not to be interpreted as placing any limitations on the scope of the claims.

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Patent claims

1. A device for selective increasing higher-order modes' losses (3) suitable for selectively increasing higher-order modes' losses in transmission systems to increase the throughput and ranges of transmission systems based on VCSEL light sources at a wavelength of 850nm, said device being in a form of an at least one optical fiber taper, executed on a multi-mode fiber at a certain wavelength, and that the fiber taper (7) has separated non-tapered optical fiber regions of (a1) and (a2) in total lengths, in which fiber diameter equals (d1); located between said non-tapered optical fiber regions, transition regions of (b1) and (b2) in total lengths, in which fiber diameter is reducing/increasing, respectively; and located between said transition regions, a taper waist region of (c) in total length, in which the optical fiber diameter is equal to (d2), and the taper level is defined as $R=((d1-d2)/d1)\cdot 100\%$ and is equal to or larger than 20%, wherein the length of the transition regions (b1) is equal to or larger than 0.5 mm, and (b2) is equal to or larger than 0 mm, and the length of the taper waist region is equal to or larger than 0.5 mm; wherein the optical fibre is composed of a core and a cladding which at the position of the transition regions (b1) and (b2) and the taper waist region (c) is coated with a filtering substance with attenuating properties and with a higher refractive index than that of the optical fiber cladding material and the fiber is multi-mode at 850nm, wherein the filtering substance is selected from: paraffin, vaseline or similar hydrocarbons, fatty acids, their salts or esters, graphite, graphene, soot, other forms of carbon and their derivatives, polymers dissolved in such organic solvents as polystyrene, ethyl cellulose, nitrocellulose, cellulose acetate, methyl cellulose, polyvinyl acetate, methyl methacrylate and their derivatives, polymers with low softening temperatures, such as polyvinyl chloride, ethylene-vinyl acetate, acrylic, octane-cellulose, butyl-cellulose polymers, polyimides, polyamides, polyolefins, perfluored polymers, R-Si-O organosols, polydimethylsiloxanes, polybutadiene rubber, ultraviolet-hardened polymers, epoxy resins, epoxy-acrylic resins, urethane-acrylic resins, silicone-epoxy resins, silicone-acrylic resins, epoxy-acrylic resins, organic fluids, such as: glycerin, toluene, styrene, carbon tetrachloride, carbon disulfide, silicone oil, concentrated

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carbohydrate solutions, immersive oil, metallic layers, metal oxides or mixtures containing at least one of the aforementioned substances or their derivatives..

2. A device according to claim 1, wherein the taper level is 97% at the most, the length of the transitional regions (b1) and (b2) is 75 mm at the most, and the length of the taper waist region is 75 mm at the most.

3. A device according to claim 1 or 2, wherein the filtering substance is applied on at least one fragment of the fiber taper (7), in the taper waist region.

4. A device according to claim 1 or 2 or 3, wherein the device for selective increasing higher-order modes' (3) is serially inserted in the structure of a multi-mode optical fiber, between at least one transmitter (1) and at least one detector (receiver) (4).

5. A device according to claim 1 or 2 or 3 or 4, wherein the device for selective increasing higher-order modes' (3) is part of an optical line of an optical fiber laser's resonance cavity.

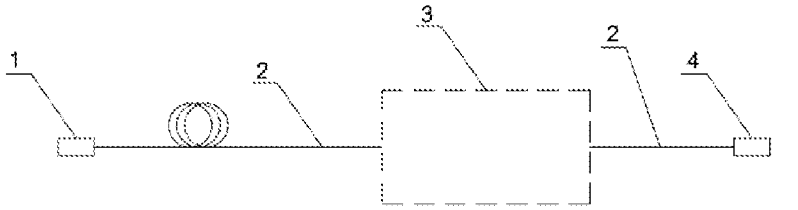

Fig. 1

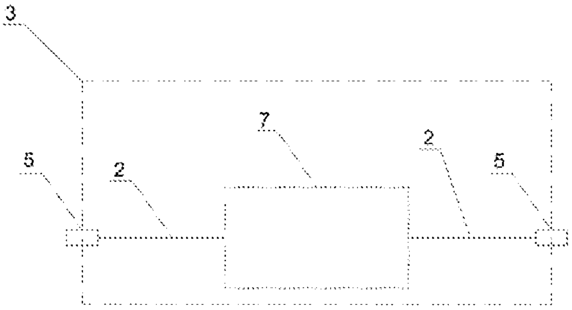

Fig. 2

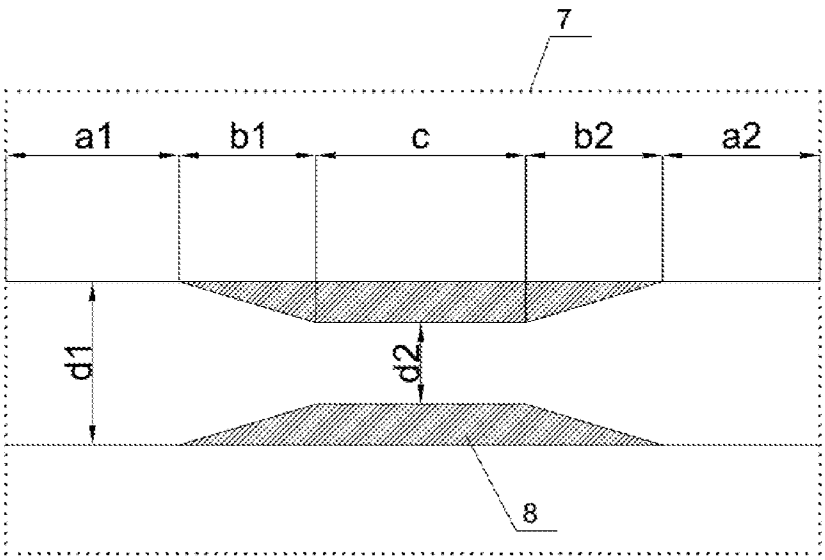

Fig. 3

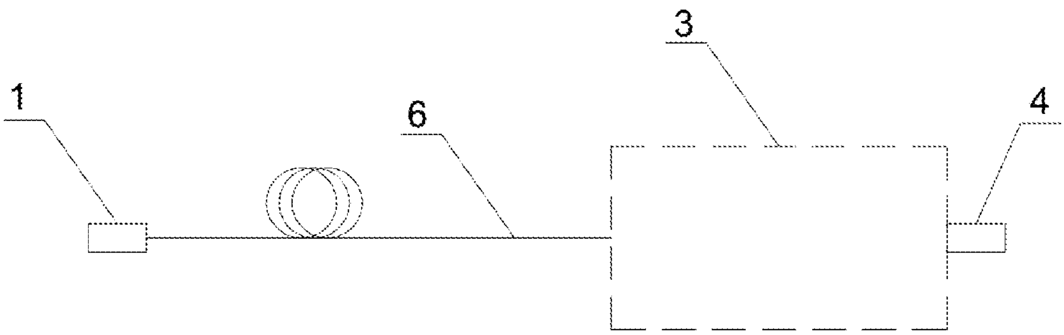

Fig. 4

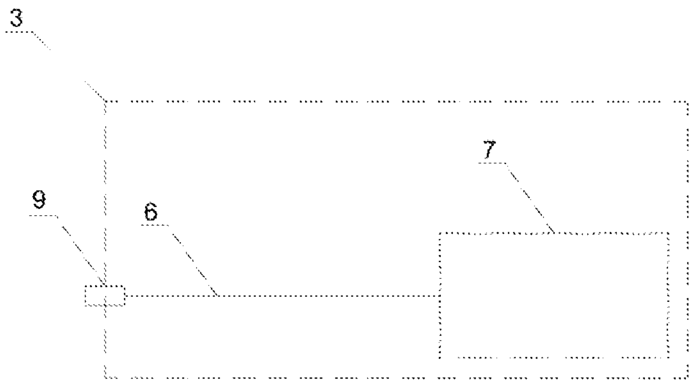

Fig. 5

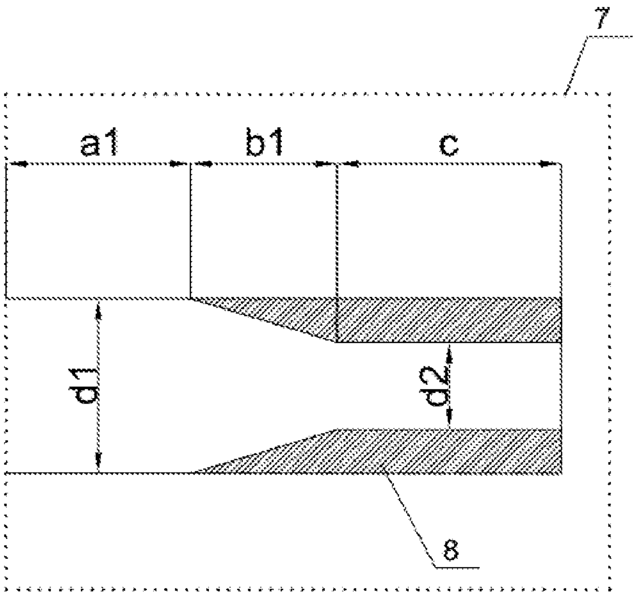

Fig. 6