*OPTICAL FIBRES*

PACS numbers: 84.60. –k; 42.81.Dp; 42.65. –k
DOI: 10.1070/QE2007v037n04ABEH013438

# Energy transfer in optical fibres

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***Abstract*.** **The possibility of energy transfer over long distances in the form of laser radiation propagating in dielectric optical fibres is discussed. Because nonlinear-optical phenomena in glasses prevent the transfer of high radiation powers in standard two-layer fibres, the outlook for this transfer is associated with the development of the technology of microstructure fibres with a hollow core and with further progress in the development of high-power fibre lasers.**

***Keywords***: *optical fibre, microstructure fibre, total internal reflection, optical losses, Bragg resonances.*

The traditional methods of energy transfer over long distances such as electric energy transfer over metal wires, energy transfer with the help of radio waves and microwave radiation are well known. The heat transfer by means of liquid carriers (for example, in centralised heating systems) requires the transfer of great masses of a carrier and therefore is considerably less efficient.

With the advent of lasers and the increase in their output power and efficiency, it became possible to transfer energy over long distances in the form of laser radiation. The efficiency of conversion of different types of energy to laser radiation energy apart, the possibility of energy transfer will be determined by specific requirements, which differ from those imposed on energy transfer in wires.

Problems related to the propagation of a laser beam in the Earth atmosphere and vacuum (cosmos) are well studied. There exist a number of restrictions on the beam power and the ultimate energy transfer distance. These restrictions are caused, for example, by self-focusing and optical breakdown in air or the diffraction divergence of a laser beam in cosmos (the farther a detector is located from a source, the large should be its geometrical dimensions). In both cases, we are dealing with energy transfer under conditions of the direct source – detector visibility.

In this paper, we analyse the promising, in our opinion, possibility of energy transfer upon propagation of laser radiation in glass optical fibres. Note first that, although both the light and electric energy belong to the same type of electromagnetic energy, this energy propagates differently in metals and dielectrics. Indeed, the electric field propagates in metals due to conduction currents, whereas the propagation of light in dielectrics is completely determined by bias currents (or the polarisability of matter). The ultimate energy that can be transferred over wires or optical fibres is also determined by different reasons. In the first case, the limiting admissible currents are restricted by losses caused by the ohmic resistance of metals. The excess over a critical current inherent in a given metal wire leads to the joule heating of the metal, resulting in an increase in its resistance, a further increase in the metal temperature, etc. up to the melting of the wire. The limiting electric current power that can be transferred in wires is characterised, for example, by the ultimate power density of no more than 220 kW $cm^{-2}$ recommended for copper wires [1].

Linear losses in silica fibres are reduced at present to the lowest level determined by the fundamental Rayleigh scattering and are $\sim 0.8$ dB $km^{-1}$ ($1.8 \times 10^{-6}$ $cm^{-1}$) at the neodymium laser radiation wavelength of 1.063 μm. In other words, the radiation power at this wavelength at low intensities will decrease by a factor of e at a distance of $\sim 5.4$ km from the fibre input. When high-power radiation is transmitted in fibres, nonlinear processes appear whose efficiency depends on the electromagnetic radiation intensity.

It is known that various nonlinear effects can appear at high light intensities even in weakly nonlinear materials such as fused silica. This concerns especially silica fibres in which, unlike bulk silica samples, nonlinear effects develop earlier than self-focusing. At present many optical phenomena determined by the light intensity are known. These are the above-mentioned self-focusing, generation of harmonics, four-wave mixing, Kerr effect, and various types of stimulated scattering: Rayleigh scattering, stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), etc. At the same time, only some of these processes are accompanied by the change in the state of the medium (its heating). Such inelastic processes are, in particular, SBS, in which a part of the electromagnetic wave energy is spent to excite acoustic vibrations in the medium, and SRS, which similarly involves the excitation of vibrational states of molecules (or groups of molecules) in the medium, as well as multiphoton absorption.

Multiphoton absorption in silica glasses is not adequately studied so far in order to compare its importance with SBS and SRS.

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Received 26 September 2006
*Kvantovaya Elektronika* **37** (4) 379 – 382 (2007)
Translated by M.N. Sapozhnikov

As for SBS and all the more stimulated Rayleigh scattering, the frequency shift and, therefore, the fraction of the electromagnetic field energy converted to heat in each scattering event in these stimulated processes are quite small. The SRS process is accompanied by a considerably larger heat release. In this case, more than 5 % of the IR photon energy coupled to a fibre can convert in each scattering event to heat.

Therefore, we can assume that the heating of a fibre in which high-power radiation propagates is mainly determined by the heat release over the fibre length caused by SRS. The estimates [2] of this heat release show that the critical intensity of the 1.063-μm radiation coupled to a single-mode fibre is $\sim 20$ GW $\mathrm{cm}^{-2}$. This value does not contradict to the optical damage threshold of fibres (above 10 GW $\mathrm{cm}^{-2}$) [3], which is at the same time noticeably lower than the electric breakdown threshold of a silica glass. These values were obtained for silica fibres with a constant and ideal homogeneity along the fibre length and the perfect structure. However, real fibres always have some deviations from the homogeneous chemical composition and perfect longitudinal geometry, which can considerably reduce the estimated thresholds presented above. Indeed, longitudinal inhomogeneities are a source of additional optical losses in which the excess heat release can be localised, resulting finally in the fibre damage. In this case, the fibre overheating and damage can be no longer related to SRS but will be determined by a strong temperature dependence of absorption (see, for example, [4]).

Estimates also show that at high intensities of the transmitted light, even in the case of good heat removal from a fibre, more than half the coupled radiation power cannot be transmitted through even a comparatively short fibre due to SRS losses. On the other hand, it is clear that the same incident radiation power can be transmitted in the linear regime (when the radiation intensity is lower than the SRS threshold) over much longer distances. For this purpose, it is only necessary to use, for example, multimode fibres or transmit light simultaneously through several single-mode fibres. As a result, a power of $\sim 1$ W (the SRS threshold) can be transmitted quite easily along one single-mode fibre, and the two orders of magnitude higher power can be transmitted along a multimode fibre. Such low powers are sufficient for a number of practical applications. In particular, fibre 'power wires' can be useful or even indispensable in cases when the application of electric wires is hazardous due to the possibility of a short circuit or the electric power is supplied in a conducting medium. An illustrative example is a system of sensors controlling the amount of a fuel in tanks of airliners. Until recently, these sensors were powered electrically, which resulted in the aircraft accident in the USA in 1996 [5]. Thereafter they were replaced by fibreoptic sensors.

Fibreoptic communication lines also find non-communication applications for transfer of low-intensity laser radiation in aerospace, military, and medical equipment. In many such applications, the light energy is converted to the electrical energy at the line output. In [6], the method based on the use of semiconductors is described, which is predicted to provide the conversion of laser radiation powers up to 20 W to electricity with the efficiency up to 60 %. The conversion of light to electricity (also by using semiconductors) with the efficiency above 50 % is reported in [7] (although for powers no more than 5 W).

So far we considered radiation at 1.063 μm. At the same time, a silica glass has minimal linear losses of about 0.15 dB $\mathrm{km}^{-1}$ at 1.55 μm. This means that the radiation power at this wavelength in a fibre with a high-purity silica core will decrease by a factor of e at a fibre length of 30 km, and by an order of magnitude at a distance of 70 km.

Certain hopes are associated in prospect with a new class of extra pure materials. Thus, it is known, for example, that some chalcogenide and fluoride glasses, in particular, based on heavy metal fluorides have fundamental Rayleigh losses at a level of $10^{-3}$ dB $\mathrm{km}^{-1}$. Therefore, having solved the problems of purification of these glasses from impurities to obtain optical losses close to the above fundamental level, as has been done in due time with silica glass, it is possible to expand considerably the possibilities of fibre optics both for communications and long-range energy transfer. At the same time, because the nonlinearity of these materials is, as a rule, much higher than that of a silica glass, the restriction on the transmitted radiation power imposed by their nonlinearity can be much more rigid. Also, new radiation sources should be found because the transparency region of the most of the above-mentioned materials lies in the spectral range between 2 and 7 μm.

Thus, we can conclude that the low-power laser radiation ($\sim 1$ W) can be transmitted along one single-mode fibre with low losses over large distances. The long-range transfer of higher radiation powers involves considerable losses caused by nonlinear effects (or the necessity of using multimode fibres or many single-mode fires).

The above discussion of the possibility of energy transfer in fibres concerns glass fibres in which the directivity of radiation is provided by the total internal reflection of light. It is clear that restrictions imposed on the limiting radiation intensity in these fibres are related to the fundamental properties of the fibre core material. At present the technology of manufacturing another class of glass fibres with a hollow core and a cladding representing a two-dimensional photonic crystal is being actively developed in fibre optics. It is obvious that threshold intensities in such fibres should be higher by a few orders of magnitude than those in fibres with a glass core.

Recall that a photonic crystal is a dielectric medium with the spatially periodically varying permittivity $\varepsilon$. The main property of photonic crystals is that, being transparent in a broad electromagnetic radiation spectrum, they have Bragg resonances and prove to be opaque in a number of frequency ranges of this spectrum. In other words, radiation with the wavelength comparable with the photonic-crystal period (period of variation of $\varepsilon$) can be efficiently reflected from this structure. In the resonance regions, radiation is localised only in photonic-crystal defects. Thus, extended defects of photonic crystal can serve as waveguides, in which the mechanism of light localisation substantially differs from the total internal reflection effect.

In practice, the two-dimensional photonic-crystal cladding of a hollow fibre is a glass matrix with cylindrical holes going along the entire fibre and arranged in some symmetric pattern in the fibre cross section. The defect of this structure, which is the fibre core, is a hole of diameter exceeding the diameter of other holes.

Irrespective of the mechanism determining the radiation directivity, the fibres of this new class with longitudinal holes in the cladding were called holey fibres (see, for example, [8]) or microstructure (MS) fibres. From the point of view of the aim of our paper, of the most interest are MS fibres with a hollow core because MS fibres with a glass core have the same restrictions as usual fibres. Physically, hollow, axially symmetric multilayer dielectric fibres (the so-called Bragg fibres) [9] belong to MS fibres. Due to their axial symmetry, Bragg fibres are quasi-one-dimensional photonic crystals because $\varepsilon$ is a periodic function of the radial coordinate only.

The common property of both these types of hollow MS fibres is that the degree of light localisation in their core can be in principle close to 100 %. This is achieved by increasing the number of photonic-crystal periods in the cladding and the permittivity contrast within the period, as well as by improving the geometry of the photonic crystal depending on the technology level. A predicted very small fraction of light propagating in the cladding determines very low material losses, so that the total losses, taking into account leaky mode waveguide losses, can be much smaller than material losses in usual glass fibres. Note that hollow fibres are potentially single-mode ones. Analysis shows that only the fundamental mode has low losses. Losses for all higher modes are greater by a few orders of magnitude, and therefore a hollow fibre is a kind of an efficient mode filter.

All the conclusions about the properties of hollow MS fibres made above are valid for 'ideal' structures. At the same time, there still exist unsolved technological and fundamental problems in manufacturing hollow-core MS fibres. As mentioned above, a high degree of light localisation in the fibre core requires the improvement of the geometry of the cladding photonic crystal. It is quite difficult to do this in practice so far because both the hole size in the cladding and the relative arrangement of the holes in the fibre cross section change during the drawing of fibres from preforms. Thus, it is necessary to develop some new technological procedures that would eliminate this effect. There also exists a fundamental unsolved problem (pointed out in [10]) which consists in the following: a hollow core is not actually a cylinder with the absolutely smooth internal surface. The matter is that during the drawing of a fibre from a preform, the spatial inhomogeneities caused by thermal fluctuations of hydrodynamic parameters (density, pressure, etc.), which are most intense in the hottest zone of a drawing furnace, are 'frozen' on this free glass – air surface. Optical losses in hollow single-mode fibres caused by light scattering by these inhomogeneities solidified on the core surface cannot be reduced at present below the value of $1-2$ dB km$^{-1}$, which was achieved in [10].

Because of a very weak nonlinearity of the air filling the core of a MS fibre, the restrictions on the intensity of light propagating in the fibre should be mainly determined by the optical breakdown in the air. The breakdown intensities, which depend on the irradiation wavelength, were measured in [11] for different gases exposed to the 0.6943-μm and 1.063 μm radiation from a ruby and a neodymium laser, respectively. The optical breakdown of air at the atmospheric pressure was observed at the intensity $\sim 700$ GW cm$^{-2}$ at 1.06 μm (which approximately corresponds to the average emission wavelength of the most high-power Yb-doped silica glass fibre lasers). By taking into account a comparatively small cross section of the mode field $\sim 60$ μm$^2$ for hollow MS fibres, which is typical for the mode field size in high-power Yb-doped fibre lasers (see, for example, [12]), we obtain that the breakdown intensity presented above corresponds to the ultimate power in the MS fibre of about 400 kW. Such powers are difficult to obtain even by solving the problem of coherent summation of radiation from several high-power fibre lasers. Therefore, at present no energy restrictions are imposed on the single-mode radiation transmitted in MS fibres.

The current level of available commercial high-power lasers can be judged, for example, from a recent report in the site of IPG Photonics [13]. According to the manufacturer, IPG Photonics sold and installed a diode-pumped 20-kW Yb-doped fibre laser at a research institute in Germany, and moreover, at present similar Yb-doped fibre lasers with the output power up to 50 kW are already available.

Note that, when the possibility of transfer of kilowatt radiation in a hollow MS fibre is discussed, the problem of conversion of such high radiation powers to electricity appears simultaneously. This problem has not been considered in the literature so far. At the same time, high-power single-mode radiation, which has a very high quality, can be directly and efficiently used, for example, for cutting, welding, drilling, and thermal processing of materials.

The modern possibilities of energy transfer in a hollow MS fibre are illustrated by the following estimate: half the radiation power coupled to a MS fibre can be transferred over a distance of $\sim 3$ km (optical losses are set equal to 1 dB km$^{-1}$). Taking into account the real conversion efficiency of the electric energy to the laser radiation energy, which is $\sim 30$ % (which corresponds to the pump efficiency $\sim 50$ % and lasing efficiency $\sim 60$ %), we obtain 15 % of the spent electric energy at the MS fibre output. The reverse conversion of this light to electricity will reduce this value approximately by half (or more). It is clear that, if optical losses in a hollow MS fibre can be reduced in the future, for example, down to 0.1 dB km$^{-1}$, the efficiencies estimated above will be achievable at a distance of 30 km.

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