from the increase in density fluctuations near the critical point of carbon dioxide gas.

Employing polarization-sensitive CARS spectroscopy revealed the spectral components of broad (on the order of 40 – 50 inverse centimeters) bands in the vibrational spectrum of a protein which are defined by the normal vibrations of the amide group. It was thereby possible to realize a new method of diagnostics of the secondary structure of protein molecules which does not rely on a priori assumptions about the band structures.

It was found out that the nonlinearity of strongly correlated systems leads to the spontaneous formation of a laser-induced 'metastable' order in them. The occurrence of phase transitions of this type accounts for the 'anomalous' results in the non-stationary laser spectroscopy of conjugate polymers, ferromagnetic films, and in a series of other objects. The spatially nonuniform excitation of ferromagnetic films by a train of ultrashort laser pulses makes it possible to 'write' in them regular domain structures defined by the light intensity distribution. A technique was realized for a non-destructive optical-acoustic verification of the state of construction materials (metals, composites) for double-sided and single-sided accesses to the object under investigation. An optical-acoustic tomograph for the early diagnosis of breast cancer was developed and fabricated.

Nonlinear-optical analogues of the Faraday and Kerr effects were discovered in the second and third magneto-induced harmonic generation at the surface of ferromagnetic materials. A giant enhancement (by 4 – 5 orders of magnitude) of the intensity of radiation at the second and third harmonics was recorded in the excitation of localized plasmons in nanostructures, as well as in porous silicon-based photonic crystals. The effect of optical Casimir nonlocality was discovered in semiconductors of a new type.

An investigation was made of the second harmonic and sum frequency generation in the reflection of femtosecond pulses from the free surface of a solution containing noncentrosymmetrical molecules. The cases of collinear and noncollinear schemes of excitation of surface electromagnetic waves of different types, which enhance nonlinear optical interaction, were considered.

A self-consistent theory of the optical response of thin and ultrathin (1 – 10 nm) metallic films was constructed. It was shown that a metallic nanometer-thick film can, under conditions of excitation of odd longitudinal collective modes, exhibit an almost total reflection of incident laser radiation.

With the aid of Raman spectroscopy, photo-induced spectroscopy, photo-induced polarimetry, and other techniques, several priority results were obtained concerning the properties and the nature of the ground and lower excited states of trans-polyacetylene on nanopolyacetylene samples, diagnostics were performed of the anisotropy of optical transitions from long-lived photo-induced states on time scales ranging from hundreds of femtoseconds to milliseconds.

An investigation was made of the feasibility of phase control of above-threshold tunnel ionization and subsequent control of the parameters of recombination radiation with the use of two-frequency laser fields. It was shown that in these fields it is possible to control both the instant of ionization (within an optical cycle) and the instant of recombination. Phase control makes it possible to generate the recombination radiation with selection of a narrow spectral range and the mode of 'enhancement' of high-order harmonics. The generation of coherent attosecond electromagnetic pulses was shown to be possible with the use of a special two-frequency pump and elliptically polarized radiation.

The scientific school of coherent and nonlinear optics created by Khokhlov and developed by Akhmanov is indeed part of the national heritage of Russia, one of the pearls of Moscow State University. In the context of the continuing deep crisis in science and education in our country, preserving this and other equally unique scientific schools is the primary concern of the MSU staff.

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Fiber lasers

E M Dianov

1. Introduction

The creation of fiber lasers is one of the most brilliant accomplishments of quantum electronics.

The first-ever fiber laser was made by Snitzer in 1963 [1]. As an active element he used an optical glass fiber containing neodymium ions. However, at that time this avenue of laser physics was not pursued and it is evident why. The advent of modern high-efficiency and compact fiber lasers was possible only owing to the development of low-loss optical glass fibers ($\leqslant 1$ dB km^{-1} in the near-IR range) in the early 1970s and the subsequent rapid development of optical fiber communication. The latter became the decisive factor in the development and industrial production of long-lived high-brightness laser diodes and a series of special optical fibers. Among them are optical fibers doped with rare-earth elements and nonlinear, photosensitive, infrared, and several other fibers. This elemental base underlay the production of fiber lasers. Of special note is the development of the technology for writing the Bragg gratings of the refractive index in photosensitive optical fibers, which are employed as distributed reflectors in fiber lasers (see, for instance, Ref. [2]).

At the same time, progress in fiber-optic communication systems with a high data transfer rate (over 1 Gbit s^{-1}) called for the development of efficient fiber lasers and amplifiers compatible with these systems. This accounts for the pursuit of extensive research and large investments for solving the problem.

The fundamental advantage of fibers as a laser medium in comparison with bulk active media resides in low optical losses, a large interaction length, and the small diameter of the fiber core (typically 4 – 20 μm), which ensures the high efficiency of pumping by the radiation of laser diodes. The large ratio between the surface area and the volume of a fiber

(~ 100 μm in diameter) radically solves the problem of heat removal, making it possible to fabricate air-cooled fiber lasers with an output power of ~ 1 kW. Of major significance for many applications is the high beam quality of fiber lasers. Employing intrafiber Bragg gratings of the refractive index as distributed reflectors ensures the compactness and high stability of fiber lasers. The above circumstances led to the development of diverse fiber lasers, including cw high-power lasers, pico- and femtosecond lasers, single-frequency lasers, Raman lasers, and several others.

In this paper I will enlarge only on recent progress in the development of high-power cw fiber lasers and lasers harnessing the effect of stimulated Raman scattering in optical fibers (Raman lasers).

2. High-power cw fiber lasers

Recent years have seen extremely rapid progress in the development of high-power cw fiber lasers (see, for instance, Refs [3, 4] and references therein). Figure 1 demonstrates the growth of the output power of lasers operating at wavelengths of about 1 μm (Yb and Nd) achieved over the last eight years. One can see that the output power rose from 30 W to ~ 1 kW during this period. Such rapid progress in the growth of output power is due primarily to the development of structurally improved active fibers and advances in the development of laser diode-based pump systems.

The schematic diagram of a fiber laser is shown in Fig. 2a. For an active fiber waveguide (*1*a), use is made of the optical fiber on the basis of quartz glass with additions of rare-earth elements such as Nd, Yb, Er, Ho, and Tm. At the present time, the widest acceptance has been gained by Yb-doped optical fibers, which provide the highest efficiency of lasing at a wavelength $\lambda \cong 1.1$ μm. Active interest is being shown in lasers which produce radiation in the 1.5 – 2.0 μm spectral range, which is thought to be safe for the human eye. In this case, advantage is taken of optical fibers doped with Er/Yb (1.5 – 1.6 μm), Tm, and Ho (~ 2.0 μm).

Neodymium fiber lasers, which lase in the spectral range around 0.9 μm, also appear to have considerable promise at present. This is due primarily to the possibility of obtaining high-power radiation in the blue spectral region by way of neodymium laser frequency multiplication. The main difficulty encountered in developing this laser is the suppression

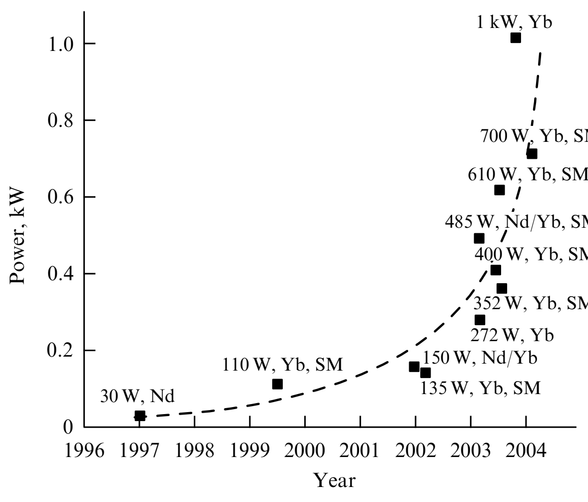

Figure 1. Growth of the output power of cw fiber lasers (SM — a single-mode laser).

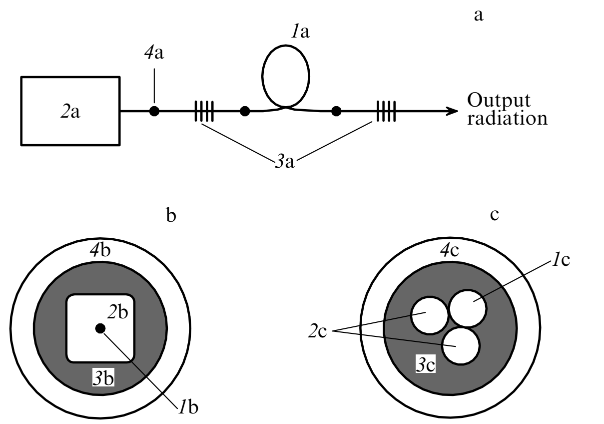

Figure 2. (a) Schematic diagram of a fiber laser: (*1*a) active fiber waveguide, (*2*a) pump unit, (*3*a) intrafiber Bragg gratings, (*4*a) fiber splice points. (b, c) Different sections of the fiber waveguide: (*1*b) fiber core containing a rare-earth element, (*2*b) first cladding, (*3*b) second cladding, (*4*b) protective cladding, (*1*c) active fiber, (*2*c) passive fibers, (*3*c) common second cladding, (*4*c) protective cladding.

of lasing at wavelength 1.06 μm, which corresponds to the stronger neodymium ion transition. Bufetov et al. [5] managed to do this by selecting a neodymium fiber design that ensures high optical losses of the fiber waveguide at the 1.06-μm wavelength. As a result, for the first time lasing was realized at a wavelength of 0.92 μm with an output power of 0.5 W for a pump power of 2.0 W at room temperature.

Of importance is the composition of the glass of the active fiber core, determining the spectral-luminescent characteristics of rare-earth elements, which define, in particular, the wavelength of pump radiation. Mel'kumov et al. [6] performed a detailed investigation of the spectral-luminescent characteristics of Yb ions in aluminosilicate and phosphorosilicate optical fibers, as well as the lasing characteristics of the corresponding fiber lasers. The photosensitivity of an optical fiber also depends on the composition of the glass of the fiber core. A relatively high photosensitivity makes it possible to write Bragg gratings (laser cavity mirrors *3*a) directly in the active fiber. Otherwise, the Bragg gratings are written in a special photosensitive optical fiber and spliced (*4*a) onto the active fiber.

As fiber-laser pump sources, use is made of individual laser diodes, as well as of laser diode arrays (matrices, linear arrays) with a fiber output. Several companies produce laser pump modules with an output power ranging from several dozen to several hundred watts. These modules possess an output fiber with a core ~ 200 μm or greater in diameter and a numerical aperture of about 0.2. Clearly, efficient input of the pump radiation into the active fiber core 5 – 20 μm in diameter and a numerical aperture of ~ 0.1 is an intricate task which calls for development of a special fiber design.

Figure 2b shows the structure of a so-called double-cladded fiber [7]. The core *1*b, which contains a rare-earth element, is surrounded by the first cladding of pure quartz glass several hundred micrometers in diameter. The first cladding in its turn is surrounded by the second cladding, ordinarily made of a polymer material with a refractive index substantially lower than that of the quartz glass. Therefore, the first cladding is a multimode light guide, which is efficiently excited by the pump radiation owing to its large transverse dimension and a high numerical aperture. Under certain values of the core and first-cladding diameters and the fiber length, the pump radiation efficiently excites the ions of rare-earth elements.

This fiber design yields good results in the fabrication of medium-power ($\sim$ 100 W) fiber lasers. For high-power fiber lasers, a fiber design was proposed wherein the pump radiation traveled through discreet fiber light guides of quartz glass (passive light guides), which are in optical contact with the active fiber, all the fiber light guides being enclosed in a common reflective cladding of a polymer material. The active fiber is excited by distributed pumping across its side surface and the number of passive fiber light guides is 1, 2, 3, or more. The pump radiation can be fed through both faces of a passive light guide, and therefore the number of possible points for the input of the pump radiation is twice the number of passive light guides. This broadens the possibilities for the realization of a high-power pumping of fiber lasers. In the English-language literature this structure of a fiber light guide is referred to as GTWave [8]. In our work [9] concerned with the development and investigation of high-power fiber lasers, advantage was taken of the light-guide structure depicted in Fig. 2c. For an available pump power of 90 W, the lasing power at the wavelength 1.07 μm was equal to 60 W, i.e., the efficiency amounted to about 65%.

Also described in the literature are other ways of introducing the pump radiation into the active fiber light guide which make use of volume elements, such as lenses and mirrors. In this case, the laser is no longer all-fiber-optical in design.

A few words about the applications of high-power cw fiber lasers are in order. At present, laser technologies are widely used in the processing of various materials, in particular for strengthening, cutting, drilling, and alloying. High-power solid-state and CO_2 lasers are employed for these purposes. High-power fiber lasers are considered an alternative to the above lasers because of better beam quality, the flexibility in laser beam transport to the object under processing, compactness, and potentially lower cost.

3. Fiber Raman lasers

The 1990s saw remarkable achievements in the development and investigation of fiber Raman lasers pumped by neodymium or ytterbium fiber lasers, which in turn are pumped by laser-diode radiation (see, for instance, review [10]).

The effect of stimulated Raman scattering (SRS) underlies an efficient technique of laser radiation frequency conversion, for the use of different materials (crystals, glasses, liquids, gases) makes it possible to obtain a Stokes frequency shift ranging from several hundred to several thousand inverse centimeters. SRS conversion is especially advantageous for the generation of laser radiation in the IR spectral range, where rare-earth solid-state lasers are low in efficiency.

Although the Raman cross section in glass is 2 – 3 orders of magnitude lower than in several crystals and liquids, greater interaction lengths, a small core diameter, and low optical losses inherent in glass optical fibers lead to efficient SRS pump-to-Stokes radiation conversion.

The first fiber Raman laser was demonstrated by Stolen et al. [11] in 1972 shortly after the emergence of glass fibers with low optical losses. For the pump radiation, the second harmonic of a pulsed Nd : YAG laser ($\lambda = 532$ nm) was used. The laser resonator was formed by volume mirrors and the pump radiation was input into the fiber with the aid of a lens. The Stokes shift in quartz glass is equal to 440 cm^{-1}, and therefore the output radiation wavelength was equal to 545 nm. It was not until the mid-1990s that efficient all-fiber Raman lasers were developed [12] owing to the rapid progress in fiber optics and optical fiber communication. In these lasers, the function of cavity mirrors was fulfilled by intrafiber Bragg gratings of the refractive index. For an active medium, use was made of a germanosilicate fiber with a Stokes shift of about 430 cm^{-1}. Pumping was performed by a Yb fiber laser generating radiation with a wavelength of about 1.1 μm.

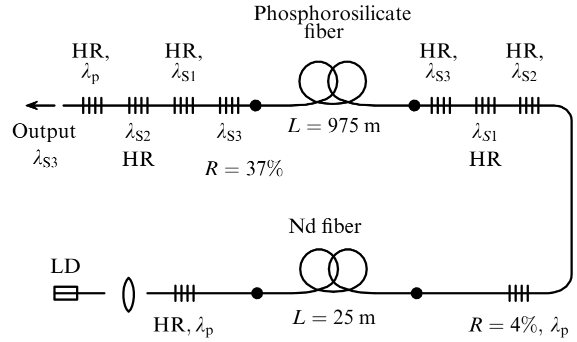

Figure 3. Schematic of an SRS phosphorosilicate fiber laser for the 1407-nm wavelength: HR — high-reflectivity Bragg grating; R — reflectivity; L — length.

While possessing a high efficiency, the newly developed Raman laser had the disadvantage of a small Stokes shift ($\sim$ 430 cm^{-1}), which required the generation of high-order Stokes components to obtain lasing in the 1.4 – 1.5 μm range. To do this required writing 5 – 6 pairs of Bragg gratings in the fiber light guide, which made the laser design much more complicated. That is why subsequent research aimed at searching for glass fibers with a greater Stokes shift. It turned out that the phosphorosilicate optical fiber has two Raman bands with Stokes shifts of 490 and 1330 cm^{-1} [13]. Employing the 1330-cm^{-1} Stokes shift allowed the design of the fiber Raman laser to be significantly simplified and made it possible to create a family of Raman lasers generating radiation at practically any wavelength in the 1.1 – 1.65 μm spectral range [10].

Figure 3 shows the schematic of a three-stage fiber Raman laser which employs a phosphorosilicate fiber and a Nd fiber laser as the pump source for generating radiation at $\lambda = 1407$ nm [14]. Pump radiation with a wavelength $\lambda_p = 1.06$ μm was efficiently converted to the Stokes radiation shifted by 1330 cm^{-1} ($\lambda_{S1} = 1236$ nm) in the resonator formed by Bragg gratings with a 100% reflectivity at the $\lambda_{S1} = 1236$ nm wavelength. This radiation in turn served as the pump for the generation of Stokes radiation shifted by 490 cm^{-1} ($\lambda_{S2} = 1316$ nm) in the resonator formed by Bragg gratings with a 100% reflectivity at the $\lambda_{S2} = 1316$ nm wavelength. Upon reaching the threshold power this radiation fulfilled the function of a pump for the generation of the next Stokes radiation component, also shifted by 490 cm^{-1} ($\lambda_{S3} = 1407$ nm) in the resonator for the $\lambda_{S3} = 1407$ nm wavelength, the output Bragg grating possessing a reflectivity of 37%. The output radiation spectrum and the dependence of the output power on the pump power are shown in Figs 4a and 4b, respectively. One can see that the output laser power amounts to 1 W, and this would suffice to pump optical amplifiers in fiber-optics communication systems.

Of considerable interest is the generation of laser radiation in the 2 – 3 μm spectral range and at longer wavelengths. Unfortunately, there is no way of employing quartz glass-

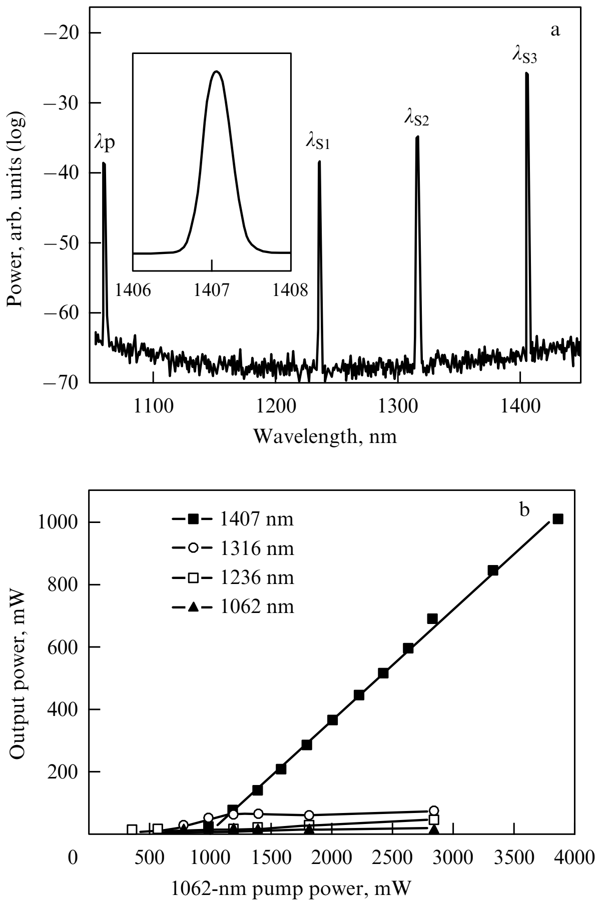

Figure 4. (a) SRS-laser output spectrum. The inset shows the radiation spectrum at a wavelength of 1407 nm on an enlarged scale. (b) Output power of the SRS laser vs pump power (Nd-laser).

based optical fibers as the active medium of Raman lasers owing to the fast growth in fundamental optical losses in this spectral range.

We have fabricated optical fibers on the basis of germanate (GeO_2) glass, which exhibits a minimum of fundamental optical losses at the wavelength $\lambda = 2$ μm and, furthermore, the Raman cross section in this glass is an order of magnitude higher than in quartz glass [15]. These optical fibers underlay the development of three- and four-stage SRS lasers which lase in the 2-μm spectral region [16]. The scheme of these lasers is similar to that in Fig. 3, except that the function of a pump laser is fulfilled by a fiber Er/Yb laser which lases at the wavelength $\lambda = 1610$ nm and a germanate optical fiber is employed in lieu of a phosphorosilicate fiber. Lasing was obtained at wavelengths of 2027 and 2200 nm with respective output powers of 900 and 210 mW for a pump power of about 4200 mW.

Therefore, a family of Raman fiber lasers has been developed, which allows lasing at virtually any wavelength in the 1.1 – 2.2 μm range, with fiber Yb and Er/Yb lasers being used as pump lasers.

4. Summary

Recent advances in glass optical fiber and laser diode technologies have led to the advent of new-generation solid-state lasers — fiber lasers. Despite remarkable progress in the development of cw single-mode fiber lasers with an output power of ~ 1 kW in the 1.06 – 1.1 μm spectral range, the output power of a cw single-fiber laser is expected to grow further and reach 10 kW.

However, to attain this level of output power requires developing new fiber structures with a large diameter of the mode field and low nonlinearity. Furthermore, the lasing spectral range of high-power fiber lasers would be expected to extend to 2 μm due to the fabrication of erbium ($\lambda = 1.55$ μm) and thulium ($\lambda = 2$ μm) lasers.

The development of optical glass fibers with a high transmittance in the IR spectral range would permit making a family of SRS fiber lasers for the 3 – 5 μm spectral range.

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On the history of the invention of the injection laser

Yu M Popov

At the P N Lebedev Physics Institute (FIAN) in 1958, on N G Basov's initiative a start was made on investigations aimed at the development of lasers. That was pioneering research pursued both in our country and abroad, along with the works of C Townes and A Schawlow in the USA.

Although molecular oscillators (masers) utilized gases, paramagnetic amplifiers of induced radiation employed crystals, which confirmed the feasibility of obtaining population inversion in solids.

That time saw rapid progress in semiconductor electronics. But the only materials which served these purposes were germanium and silicon, the use of silicon being still in its infancy. At FIAN, the properties of semiconductors in strong