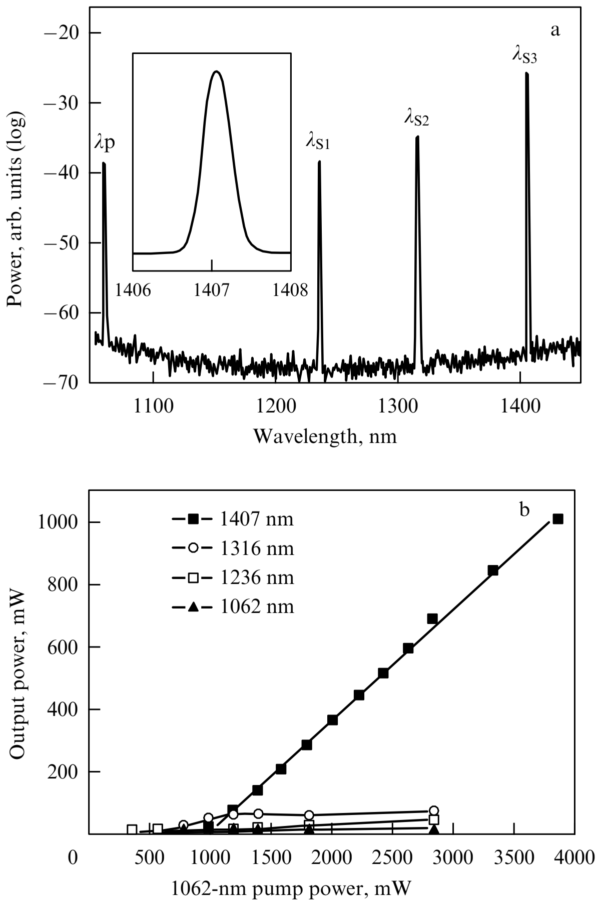

Figure 4. (a) SRS-laser output spectrum. The inset shows the radiation spectrum at a wavelength of 1407 nm on an enlarged scale. (b) Output power of the SRS laser vs pump power (Nd-laser).

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 electric fields were investigated in the Semiconductor Physics Laboratory supervised by B M Vul. Basov and his collaborators turned to Vul and his colleagues to discuss the feasibility of producing population inversion in semiconductors required for the amplification of light.

As the first step, Basov, Vul, and Yu M Popov submitted an application for an invention (1958) and published a paper concerning the use of short current pulses for the avalanche multiplication of current carriers from the valence band (or from impurities), which produce, when cooled by the lattice, population inversion [1].

Since interband avalanche multiplication in germanium and silicon necessitated high field intensities and optical interband transitions were indirect, experimentally it was decided to work on the ionization of impurities in these materials and realize interband ionization using narrow-gap semiconductors with direct (vertical) optical transitions.

At that time, the most extensively studied semiconductor of this kind was indium antimonide, which was grown in the Leningrad Physicotechnical Institute (LPhTI) in Prof. D N Nasledov's laboratory.

With his inherent enthusiasm Basov assembled his collaborators and, taking advantage of every opportunity, organized visits to Leningrad. That time is well retained in my memory: in the late 1950s, in a sharp frost we (including Basov) repeatedly spent the night in the academic hotel in Khalturin Street in a room which accommodated no fewer than ten other people sent on the mission.

A scientific group in the Semiconductor Physics Laboratory was engaged in the observation of luminescence in the recombination of electrons ionized from shallow impurities in germanium and a group in the Laboratory of Oscillations in the observation of emission in the avalanche multiplication in indium antimonide. However, although this research yielded interesting scientific results, no indications of stimulated emission were observed. The main difficulties were the necessity to produce current pulses with very short rise times and to work in the infrared region. However, not only did these difficulties fail to weaken Basov's resolve, but they put heart into him. He got several other optical laboratories of FIAN to take part in laser research.

Almost daily Basov would discuss the laser invention problem for hours with the theoretical group of which O N Krokhin and I were members.

In 1960 we published a large paper in *Usp. Fiz. Nauk*, which reviewed the principal methods and media for making lasers and contained a number of original ideas for using semiconductors for this purpose [2]. In particular, population inversion was formulated as a condition for the nonequilibrium distribution functions in the bands, and it was suggested that the resonator be formed by the parallel natural output sides of the semiconductor, whose reflectivities are high enough to provide feedback. Early in 1961 we proposed a method for producing population inversion employing fast electrons and in March came up with the idea of obtaining population inversion by injecting nonequilibrium current carriers across the p – n junction of degenerate semiconductors and formulated the principal conditions for it [3]. The paper stated that the pump current is diffusive, and its magnitude was correctly estimated and the continuous regime was predicted to be feasible; the spacing between the Fermi quasilevels should exceed the energy gap width; use should be made of semiconductors with direct radiative transitions; and diffraction losses will be decreased

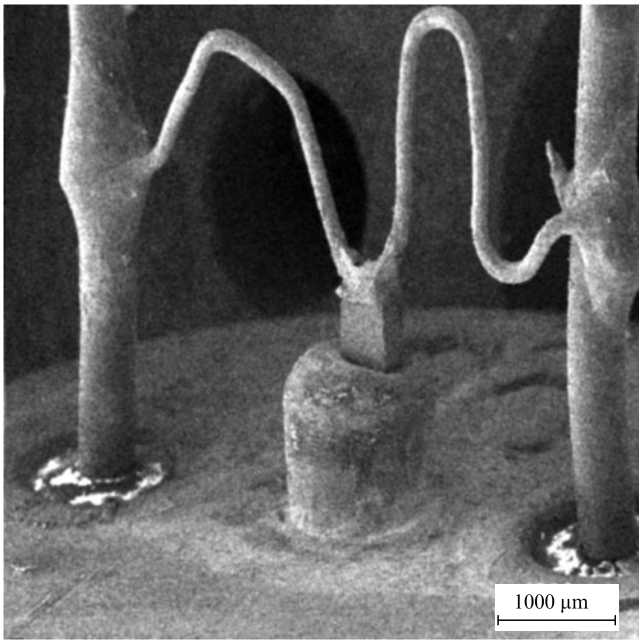

Figure 1. Photograph of the first injection laser in the USSR (FIAN, December 1962).

owing to the large refractive index of the active region. It was also indicated (even at that time) that the current density required to produce inversion may be lowered through the use of semiconductors with a different energy gap width.

Even to us the idea of making a laser by way of diode operation in the forward direction seemed to be extraordinary and at the same time rather simple. Interestingly, when this paper was reported to a seminar, doubts were cast on the consistency of this idea with the second law of thermodynamics. Vul suggested that we should not publish this paper until obtaining experimental results. We nevertheless published our proposal in the June issue of *Zh. Eksp. Teor. Fiz.* in 1961, and a start was made on experimental research in this area.

We recounted the p – n junction laser concept to many audiences throughout 1961 and in the first half of 1962. Staying on an exchange visit in the USA from October 1961 through March 1962 I spoke at a seminar at Harvard University, where N Bloembergen asked me questions about mode-type selection. In January 1962, after a report at Columbia University, I had a long discussion with IBM scientists P Sorokin and M Nathan; at the end of the same year, the latter was one of the first to obtain stimulated emission from a p – n junction in gallium arsenide. In a review paper published in 1964 [4] G Burns and Nathan referred to our papers [1, 2] as priority works as regards the idea of using semiconductors for the generation of light and to Ref. [3] as the first-ever proposal to make an injection laser.

In September 1961, after a report at a conference in Tashkent Krokhin and researchers from LPhTI considered their performance of an experiment with a gallium arsenide diode which was at their disposal. They accomplished it early in 1962. In the April issue of *Fiz. Tverd. Tela* (Leningrad) in 1962 [5], D N Nasledov, A A Rogachev, S M Ryvkin, and B V Tsarenkov reported the observation of narrowing of the spontaneous emission line with increasing pump current. As a possible explanation for this effect they indicated the partial presence of stimulated emission in accordance with our work [3].

In the November issue of *Phys. Rev. Lett.* in 1962, R Hall et al. of General Electric reported obtaining coherent radiation from the p – n junction in gallium arsenide [6]. Almost simultaneously, three other US laboratories reported the operation of first injection lasers [7 – 9]. In December, as a result of the collaboration of two groups supervised by Basov and Vul, the first USSR p – n junction laser was made at FIAN.

More than 40 years have passed since that time. It is no exaggeration to say that several 'scientific and technical revolutions' have taken place in the development of injection lasers during this period: the use of heterojunctions in three- and four-component solid solutions, extension of continuous room-temperature operation to 100 years, obtaining direct electric energy conversion to coherent light with an efficiency up to 70%, achieving an output power above 10 W, and the development of injection lasers in the blue-green and violet spectral regions with the use of nitride compounds. A large contribution to this progress was made by LPhTI and FIAN scientists under the supervision of Zh I Alferov and Basov. These accomplishments have underlain contemporary scientific and technological progress in the areas of fiber-optics communication, high-density memory in optical disks, high-resolution spectroscopy, efficient pumping of solid-state lasers, etc. Evidently, the role of injection lasers will increase still further in significance, for the most 'bold' opinions promise that they will replace all existing means of illumination.

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