SINGLE-MODE TRANSMITTING MODULES FOR FIBER-OPTICS LINES OPERATING AT WAVELENGTHS 1.3 AND 1.55 μm

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Optoelectronic sources for the 1.3- and 1.55-μm bands have been developed on the basis of InGaAsP/InP heterostructures in the form of modules that include a Peltier microcooler, a temperature sensor, and a photodiode monitor. The properties of single-mode sources are presented and the technique of is discribed of coupling them to single-mode fibers using a taper and a microlens lightguide pigtail. Data on the influence of parasitic and some results on high-frequency modulation and information transmission are given.

INTRODUCTION

Proper use of injection semiconductor lasers for information transmission requires satisfaction of a number of conditions that ensure stable and prolonged operation of the active element. These conditions include:

– effective and well-stabilized coupling of the laser emission to the optical-channel elements, particularly to the fiber lightguide.

– stabilization of the operating regime (radiation power, temperature, wavelength, etc.) of the active element,

– coupling-in a high-frequency signal for direct modulation of the radiation,

– mechanical protection of the active and other elements, and sealing them in an inert atmosphere.

Added to these conditions are sometimes elimination of parasitic feedback from the optical channel, integration with other elements such as those used for external modulation and with microelectronic circuits, etc. These and other requirements can be taken into account and implemented in laser-emitter modules.

Some experience with the development of relatively simple and sufficiently reliable laser modules for the 0.85- and 1.3-μm bands was gained as a result of joint development work by the Lebdev Physics Institute, the Central Institute of Optics and Spectroscopy of the Academy of Sciences of the GDR, and the Physics Institute of the National Research Center of the Vietnam Socialist Republic. Development of one of the first laser amplifying modules for the 1.3-μm band is reported in a sequel to these studies [4]. We present here the results of developments and of research into single-mode laser modules for the 1.3- and 1.55-μm bands, intended for use in later generations of communication systems (i.e., based on a single-mode fiber-optics cable using digital modulation of the intensity and direct photodetection). Estimates will be presented on the quality of the information transfer based on results of mock-up tests of laser modules for an optical cable up to 30 km long.

The modular structure of the developed emitters inludes:

– a 1.3- or 1.55-μm laser diode (using a low-threshold buried InGaAsP/InP stripe heterostructure),

– a fiber-optics lightguide with matching (microlens) device,

– a monitor photodiode illuminated by the rear end of the laser diode,

– a thermoelectric microcooler (a stack of Peltier elements),

– a temperature sensor (thermistor or thermometric diode).

Such an assembly ensures reliable inclusion of the coupling device for feeding the laser radiation into the lightguide, the possibility of recording or automatically monitoring the optical power of the emitter against the photodiode-monitor signal, thermal stabilization of the active element with the aid of microcoolers in response to the temperature sensor, and suitable mechanical and chemical protection of the working elements.

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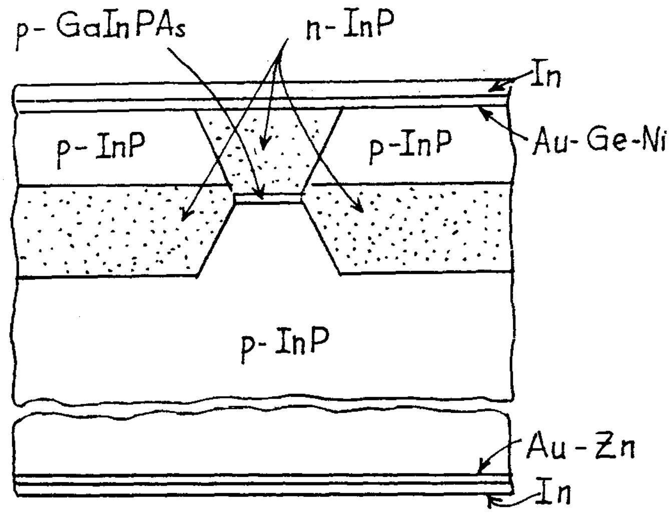

Fig. 1. Diagram of laser diode with buried mesastripe structure (BMS) based on an InGaAsP/InP heterosystem on a *p*-type substrate.

1. ACTIVE ELEMENTS OF LASER MODULES

For a number of considerations, principal among which is minimization of the damping and of the spreading of short light pulses, the 1.3- and 1.55-μm bands are preferred for fiber-optics communication systems (see, e.g., the review [5]). An almost ideal source of optical signals for these bands are injection lasers first implemented in [6] and based on the InGaAsP/InP heterostructure. By varying the chemical composition of the active radiating region in such heterostructures it is possible to vary the emission wavelength in the wide interval from 1.1 to 1.67 μm which evidently contains the above optimal wavelengths. An injection laser based on a heterostructure acts not only as a carrier-frequency generator, but also as a modulator, since it permits wide-band direct modulation of the pump current.

Other advantages of injection lasers are such properties as effective direct conversion of electric energy into coherent radiation (the efficiency reaches 20-30% at times), durability (the operating lifetime can exceed 10^5 h), compatibility with the usual semiconductor-microelectronics circuits (operating voltage 1.5-2 V, operating current 30-80 mA), exceptional compactness (active-medium volume 10^{-10} cm^3, semiconductor chip volume 10^{-5} cm^{-3}).

The most widely used in laser communication are the so-called buried heterostructures with stripe geometry, one of the most successful modifications of which is described in [7]. In such heterostructurs the narrow active region is bounded in the lateral directions by heterojunctions (see Fig. 1) and serves as a dielectric 3D waveguide for the generated radiation. Owing to the presence of confined ("antiguiding") *p–n* junctions or high-resistivity layers, the buried regions prevent the pump current from spreading over the total cross section of the semiconductor chip and concentrate the current in a stripe "window" that coincides with the active region. The threshold current in lasers of this type ranges from a few to tens of milliamperes (room-temperature lasing was obtained in [8] at 4-5 mA). A distinctive feature of the heterostructures described in [7] is that they are produced on *p*-InP substrates. This version was used as the basis in the present investigation.

The mode composition of the emission of a buried heterostructure (BH) was investigated in [9], where it was shown that to produce a single-mode active waveguide with buried indium phosphide it is necessary to decrease the width of the active region (to less than 3 μm). This decrease ensures stable single-mode generation and can operate with lower threshold and working currents. Analysis of a dielectric waveguide in a BH-laser has shown that decreasing the thickness of the active layer to less than ~0.1 μm makes it possible to increase the critical width of the active stripe (i.e., the width corresponding to cutoff of the first-order modes). This is sometimes useful for increasing the optical power or for lowering the requirements with respect to the deviations of the width from the specified value, thereby increasing the output of usable single-mode samples.

A useful version of low-threshold heterostructures are those with the so-called "separated confinement" or with "three-layer waveguides"; as for the InGaAsP/InP heterosystem, structures of this type with an ultrathin active layer are desribed in [10]. In "three-layer" waveguides the active layer is only the central one, likewise made of the quaternary compound InGaAsP, but with a larger band gap than in the active layer.

TABLE 1. Calculated Values of the Critical ("single-mode") Width of the Active Stripe in a Buried Heterostructure Emitting at a Wavelength 1.3 μm (the waveguide layers are assumed to emit at 1.06 μm)

Total width of three-layer waveguide (μm)		0,I	0,2	0,3	0,4	0,5
Critical width (μm)	0,05	2,I0	I,55	I,30	I,I5	0,95
at an active-layer thickness (μm)	0,I	I,45	I,I5	I,03	0,9I	0,85

The threshold current density in a heterostructure with a three-layer waveguide is substantially lowered, as shown, in particular, in [10]. Judging from the results obtained in [10] for heterostructures grown by liquid-phase epitaxy, the optimal active-layer thickness ranges from 50 to 80 nm. The attainable threshold current density is then 0.5 kA/cm^2 and the threshold current of stripe lasers can be lower to several milliamperes at room temperature.

In heterostructures with a three-layer waveguide, the condition for cutoff of high-order transverse mode, i.e., the "single-mode" condition for a dielectric buried-structure stripe waveguide, can be modified by substantially decreasing the thickness of the active element proper. The limiting width obtained for a single-mode waveguide from calculation by the effective-refractive-index method is given in Table 1.

It follows from the calculation, in particular, that the width limit of a single-mode waveguide in a three-layer configuration is smaller than in ordinary binary heterostructures with the same active-medium thickness. If, on the other hand, these widths are compared at an active-layer thickness equal to the total thickness of the three-layer waveguide, the limiting width for the three-layer configuration turns out to be larger.

In practice, lasing in a zero-order mode can be observed also at a width larger than critical [9]. The reason is the ability of the lower mode to compete near the cutoff width of the first mode. However, when the critical width is increased, the probability of excitation of the first mode is increased. A jump of the generation from a zero-order mode to a first-order mode is sometimes observed when the pump current is increased. The width of unstable generation in the zeroth order, according to the data off [9], was about 3 μm for buried binary heterostructures with active-layer thickness 0.12 μm. Thus, to achieve predominance of single-mode lasers with stable operation in the zeroth-order mode it is useful to limit the width of the active stripe to about 2 μm in the case of ordinary binary heterostructures and to about 1 μm for heterostructures with three-layer geometry (at an active-layer thickness 0.05-0.1 μm and a three-layer waveguide thickness not more than 0.3 μm). These values have limited reproducibility in practice, so that to detect and reject "non-single-mode" active elments (prior to constructing the module unit) it is advisable to monitor the directivity pattern of the radiation (e.g., by displaying the far-field pattern with an electrooptical converter [9]). Generation in high-order modes is easily revealed by the presence of two or more spots (stripes) in the far field.

Typical dimensions of laser chips used in the present study were 400 × 250 × 100 μm (cavity length 250 μm). The mirror faces were produced by spalling along (110) cleavage planes, whereas the active-layer plane was oriented near (001), while the direction of the active stripe coincided with [110].

Serviceable samples of semiconductor chips were selected in accordance with the following rules. The primary selection was based on an estimate of the morphology of the active element, by visual monitoring with an optical microscope. The selection criterion was the absence of visible growth defects, such as growth grooves, unburied regions and growth pits near the active stripe, and also growths protruding from the chip surface (and capable of preventing flush soldering of the chip to the contact plate). In addition, visual inspection can detect chips with imperfect cleavages in the region where the active stripe emerges to the end faces, and with other visible flaws. Among the undesirable defects of buried heterostructures are growth pits that can be distributed over the entire surface of the chip, including also far from the active stripe. They are harmful because after metallization of the chip, shunting bridges are produced over the walls and at the bottoms of the pits and deteriorate the insulation in the growth regions. The corresponding leakage currents are added to the threshold current and influence the slope of the watt—ampere characteristic at a current higher than the threshold value. Growth pits have characteristic dimensions in the range 3-5 μm, so that their observation calls for the use of increased optical magnification.

Experiment shows that the permissible number of pits of this type is not more than 10-20, although no direct dependence of the leakage current on the number of visually observable growth pits has been obtained.

The next stage in the selection of suitable chips is to monitor the lasing chracteristics, and is effected after mounting the chips on the contact plate and soldering the upper (wire) contact. The procedure includes determination of the threshold current J_t and of the working current J_p needed to obtain a specified optical power P, and observation of the far field of the radiation. A typical selection variant requires satisfaction of the following criteria:

1) $J_t < 45$ mA.
2) $J_p < 80$ mA for $P \geq 3$ mW.
3) Stable lasing patterin in the zeroth-order mode between J_t and J_p.

Lastly, the third stage of selection of suitable chips consists of short-duration thermal-current tests to detect hidden faults, i.e., possible short life of the samples. Sometimes such a test is called "burning out" the defective article and is carried out under accelerated degradation conditions by raising the operating temperature (this leads automatically to an increase of thw working current by virtue of the temperature dependence of the threshold current). Heating-current tests are useful both during the chip-selection stage and after complete assembly of the module (the second control is not so much of the chip as of the coupling units and the contacts of the device). A typical reject burn-in is performed at:

1) $P = 1$ mW.
2) $T = 313$ K.
3) $t = 3$ h.

The samples passing the test are only those whose working parameters J_t and J_p vary in the range ±5% (when measured at room temperature or at the test temperature). It is known that to select emitters meeging more stringent longevity criteria (for example, for underwater or surface communication systems with autonomous repeaters) the heating-current tests are much more stringent (temperature up to 343 K, duration from 100 to 3000 h).

Besides technological failure due to imperfect soldering of the semiconductor chip, rapid degradation is caused also by internal defects in the laser structure, which cannot be detected visually or by one-time measurements of the laser characteristics. Internal degradation processes proceed at a wide range of rates, some idea of which can be gained from the results in [11]. The fraction of long-lived samples with acceptable initial degradation (or showing no such degradation) was not less than 40% of the studied contingent, according to extrapolated failure-free operation of not less than 10^5 h, but for 30% failure within not more than $2.5 \cdot 10^4$ h could be predicted. These estimates have a direct bearing on our work, since they pertain precisely to the BH lasers on p-substrates, which were used in the module devices. Thus, prolonged tests in an accelerated regime are needed to select the samples having the longest life. Tests at 100°C for 100 h are recommended in [11], but lasing at 100°C is achieved only by samples with the lowest threshold (less than ~20 mA at room temperature). No equivalent test conditions are therefore produced for the usual contingents.

The selection criteria discussed above do not include requirements with respect to the spectral makeup. The reason is that the procedure used to prepare heteroepitaxial structures usually guarantees wavelengths in the 1.3 ± 0.05 μm range which is accessible for most applications. As to the width of the laser-emission spectrum, we are dealing so far with information transmission at a carrier wavelength close to a point where the dispersion in the lightguide material (SiO_2) is a minimum, i.e., about 1.27 μm, and the spectrum width does not influence substantially the limits of the transmission rate. Therefore selection based on the single-frequency or multifrequency attribute offers usually no benefits. This does not mean that monitoring the spectrum can be completely dispensed with. Classification by wavelength is required in those cases when the transmitter is matched to the receiver in a narrow spectral band (for example, when spectral channel narrowing, or devices with increased interference immunity, are used). Monitoring of the spectral composition of the radiation (the permissible number of longitudinal modes of comparable intensity, or the permissible width of the spectrum profile) is advisable to obtain systems with minimum noise. It turns out then that the single-frequency regime, which is indispensable in coherent communication systems, must be stabilized to a high degree, whereas in most incoherent system it either offers no advantages or is simply undesirable because of the excess noise (due to interference in the optical channel and in the case of mode switching in the active element itself).

In BH lasers, the typical behavior of the radiation spectrum has been well investigated and cannot be substantialy altered without additional measures to modify the cavity (external C^3 laser, elongated, transparentized, etc.). The usual result is a multifrequency pattern at the lasing threshold, narrowing of the spectrum profile when the pump is increased, and a subsequent broadening of the spectrum due to the onset of nonstationary generation (self-modulation or a spike regime). Narrowing of the spectrum leads frequently to the onset of a single-frquency regime that can be tracked in the pump range from about 20% above threshold to a twofold and larger excess. Since the required power is usually not less than 3 mW

TABLE 2. Comparison of Variants of Laser—Lightguide Coupling Unit

Characteristic	"Discrete" variant	"Integral" variant
Adjustment tolerances	Large	Small
Input efficiency	30%	50-70%
Possibility of introducing additional discrete elements	Present	Absent
Couplings	Moderate	Low
Sensitivity to mechanical action	High	Low

(ahead of the coupling into the waveguide) and this calls for exceeding the threshold by 1.5-2 times, the determination of the spectral composition at a given power can serve as a basis for distinguishing between single- and multifrequency samples. Recognizing, however, that the coupling device influences he lasing regime by introducing a difficultly controllable parasitic feedback, it is best to effect such a classification after assembling the module.

2. MATCHING THE ACTIVE ELEMENT TO THE LIGHTGUIDE

The requirements on the unit that matches the laser to the fiber lightguide (coupling-in unit) reduce to the following):

— effecitve input of the laser emission into the lightguide;

— stability of the input efficiency to thermal cycles, prolonged operation, and prlonged storage;

— minimization of parasitic reflections that affect the lasing regime in the active element.

Alternative approaches to the coupling-unit design are based on two technical variants:

1) inclusion of a lens collimator,

2) use of a microlens obtained by reshaping the end of the lightguide.

The first variant, sometimes called "discrete," is useful in dismountable units. It is customary to use spherical microlenses one of which is fixed at the focal length near the laser and forms a roughly collimated beam. This beam is captured by a second spherical lens and is focused on the end face of the lightguide. An optical connector can be formed on collimated-beam section of 0.2-1 mm diameter, since the tolerances with respect to the transverse and longitudinal displacements of the second lens from the beam axis are compatible with the mechanical tolerances of the connector (about 0.05 mm). The comparative properties of this connector are listed in Table 2.

The second, "integral" variant is based on the use of a microlens configuration of the end of the fiber lightguide, obtained by melting or selective etching, and located in the immediate vicinity of the transmitting mirror of the laser. This variant is the principal one used in the module devices considered here. Its advantages over the discrete variant are, as seen from Table 2, a higher input efficiency, a low parasitic-reflection level, and a low sensitivity to mechanical action. On the whole, the coupling unit is a rigidly fixed structure suitabble for devices having fiber-optics (nondisconnecting) leads of the pigtail type. We must emphasize the shortcomings of this variant, namely, low (fractions of a micron) tolerances in the mutual adjustment of the laser and lightguide, and impossibility of introducing an optical insulator to prevent entry of parasitic reflections from more remote junctions of the optical channels into the active element. This means that the modules described here remain exposed to reflected signals, and the influence of the latter on the lasing regime cannot be neglected. Some data on this subject will be given below.

The end point of the fiber lightguide was shaped by softening and melting in a spark discharge [1]. The lightguide is initially drawn to a diameter determined by the desired diameter of the microlens (the length of the drawn section — the phocon — is 0.2-2 mm). Spalling in the narrow section of the lightguide was by local heating with a spark; the flat end face was then melted to form a hemisphere. This method yielded microlenses with curvature radii 2-60 μm (samples are shown in Fig. 1). To prevent interference efects in the phocon part of the lightguide, effects especially noticeable in the presence of

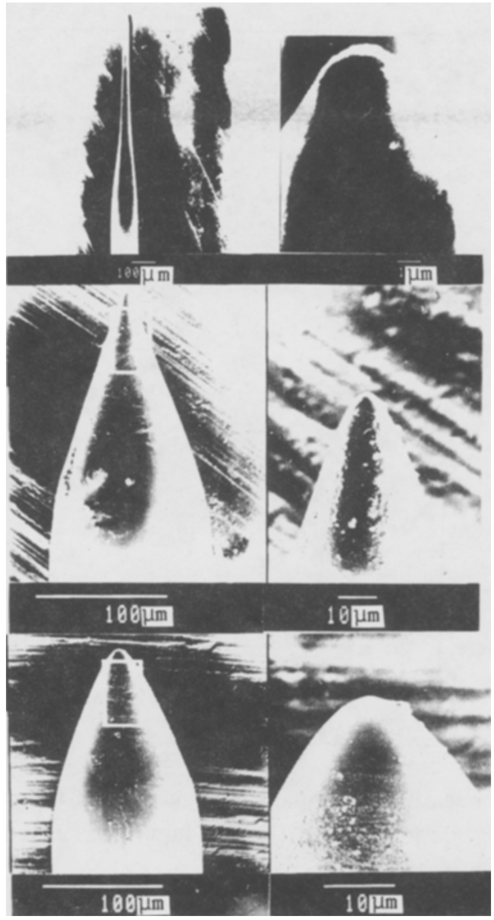

Fig. 2. Several types of microlenses at the end of a fiber lightguide (on the right — in enlarged scale).

dispersion of the refractive index in the central part of the lightguide sheath, the length of the section with variable diameter was made minimal — not more than 500 μm.

The input efficiency η was determined by measuring the optical power at the exit from the lightguide segment (Φ_I) and at the exit from the laser (Φ_O) from measurements made prior to the coupling. The influence of the feedback was consequently neglected, a procedure justified by the absence of changes of a threshold current after the coupling. The input efficiency $\eta = \Phi_I/\Phi_O$ depended on the individual features of the lasers and of the microlens, so that to obtain the best results it was necessary to carry out an empirical optimization by selecting the microlens devices to fit each active element. Figure 3 shows the watt–ampere characteristics of the laser, measured before and after the joining — through a single-mode lightguide. The active element had an approximate threshold current 40 mA and a differential watt–ampere efficiency 0.18 W/A from one face. After the coupling, the slope of the characteristic decreased (see curves 1 and 2), and the input efficiency was 62% in an interval up to a twofold excess above threshold, followed by a decrease (to ~59% at 100 mA) due to some deformation of the laser-emission directivity pattern. Such changes of η as functions of the pump are quite typical, namely, the maximum input efficiency is reached at small (up to twofold) excess above threshold, and decreases to 5-10% with further increase of the pump.

The small tolerances in the adjustment of the coupling unit call for the use of a precise adjustment, particularly the use of piezoelectric moving elements, and require also the use of low-shrinkage adhesives to preserve the adjusted state. Some ideas concerning the input-efficiency sensitivity to transverse waveguide dimensions is given by Fig. 4, which shows a two-dimensional matching pattern obtained by piezoelectric scanning of a microlens lightguide (microlens radius 2 μm) near the end face of a laser operating at 1.3 μm wavelength and having a radiation spot measuring 1.5×1.0 μm. A Gaussian whose parameters were determined by the best-fit method was used to approximate the experimental distributions. The principal sections of the two-dimensional figure shown in Fig. 4 have a width 1.5-2 μm FMHW at 50% efficiency of matching at the peak.

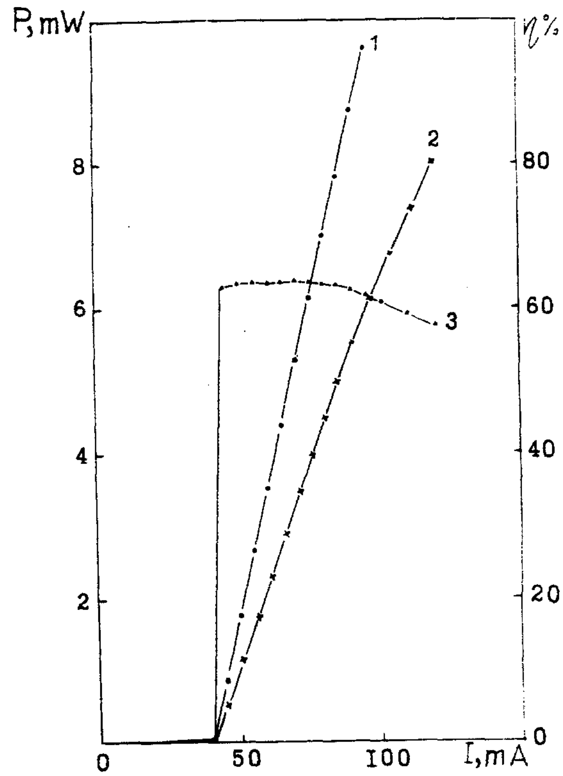

Fig. 3. Output power of the laser-diode emission (1), of the single-mode fiber lightguide joined to it (2), and input efficiency (3).

The decisive step in the production of the coupling unit is securing the adjusted state so as to prevent displacements by 0.5-1 μm. Polymer adhesives or metallic solders are used for this purpose. The use of solder calls for preliminary metallization of the lightguide section in the immediate vicinity of its end face. In both cases it is necessary to minimize the inevitable shrinking of the fixing compounds, which occur when the adhesives polymerize or the solders solidify. Contributing to this is optimization of the compositions so as to minimize the physical shrinkage. However, the coupling unit should ensure minimization of the thickness of the fixing material between the lightguide and the surface of the support. Obviously, the adhesive variant is simpler and consequently relatively cheaper, whereas the metallic variant improves the reliability and longevity of the coupling unit. Both variants can therefore be used, depending on the particular task.

In the first variant one chooses carefuly an epoxy-resin composition with minimum shrinkage, and a preparation method that results in reproducible shrinkage. The adjustment cycle must include a lead time for the expected shrinkage, so as to obtain maximum input efficiency at the instant of final fixing of the coupling unit. These measures, and the relative simplicity of the coupling unit (the base is a contact plate on which the active element is joined), make it possible to decrease the influence of the adhesion procedure on the input efficiency to a negligible shift not exceeding 5%. Figure 5 shows an example of a two-sided coupling of an active element with lightguides, suitable not only for emission modules, but also for amplifiers and optical switches on their basis.

3. MODULAR DEVICES

Depending on the character of the laser-source applications, the modular devices required vary in complexity. For autonomously operating transmitters and for repeaters it is advantageous to use modular devices containing in addition to the laser diode, and the lightguide matched to it, also a monitor photodiode, a Peltier thermocouple, and a temperature sensor. This assembly is contained in the modules LM-1300 and LM-1550, the external view of which is shown in Fig. 6a, and the arrangement of the elements in the housing is shown schematically in Fig. 6b. For these modules, which differ only the laser-diode wavelength bands, there was specially developed a miniature 24-element Peltier microcooler of mass 1.2 g, capable of cooling by 30-40°C at a current up to 0.5 A (in the nominal laser-diode regime, i.e, at a pump current not exceeding 100 mA). It is possible to place in the modue housing also the industrial TEMO-8 microcooler.

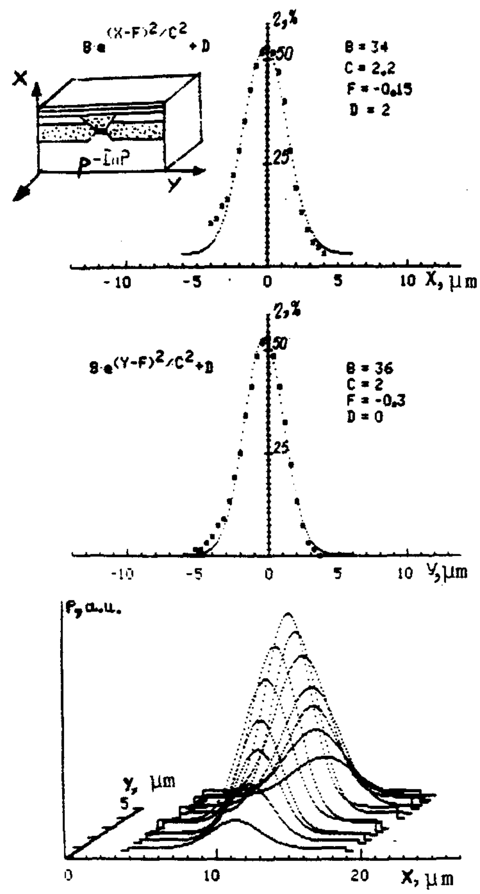

Fig. 4. Dependence of the radiation output power at the exit face of the lightguide on the displacement of the lightguide in the x and y directions relative to the laser diode.

The temperature sensors used were optically insulated semiconductor diodes fastened to a coolable (heat-conducting) surface of a thermocouple in the immediate vicinity of the laser diode. The monitors were unenclosed germanium photodiodes or phototransistors operating in the diode regime, suitable for the 1.3- and 1.55-μm bands without replacement of the sensitive element. A summary of the characteristics of the module units is given in Table 3. Both modules can be revamped to use a lightguide that preserves the polarization, or a multimode lightguide, if necessary. The module housing measures 12 × 12 × 8.5 mm, and the mass (without the fiber cable) of the assembled module is 6.5 g. The modules have 8 electric lead-ins compatible with the microcircuit panel. The length of the fiber-optics cable is 100-150 cm, the diameter of the light-conducting core is 7 ± 1 μm, the outside diameter of the lightguide is 125 ± 5 μm, and that of the optical cable is 8 mm.

For use in test appratus and for experimentation, it is advantageous to choose the simplest modules, whose composition is given in Table 4. In particular, they contain no microcooler and are designed for use with external thermal-stabilization devices.

The laser diodes for the modules have an appreciable technical lifetime (not less than 50,000 h), and cases of their untimely failure are usually due to poor technological quality control (faulty mounting of electrodes, faulty soldering of the diode to the heat-dissipating plate, macrodefects in the diodes, and chemical-metallurgical processes due to an excess of solder). Other causes of failure can be overloading due to operation beyond the recommended regimes, and hence not included among the factors that limit the technical lifetime. Rejection of potentially short-lived samples can be based on short-duration tests at increased temperature ("burning in" the reject). The final test of the assembled modules consists of operating for 3-4 h at 40°C at 1 mW power. The rejection criterion is a power decrease to below 90% of the initial value. The expected liftetime of modules passing such tests is estimated at 10^4 h and more.

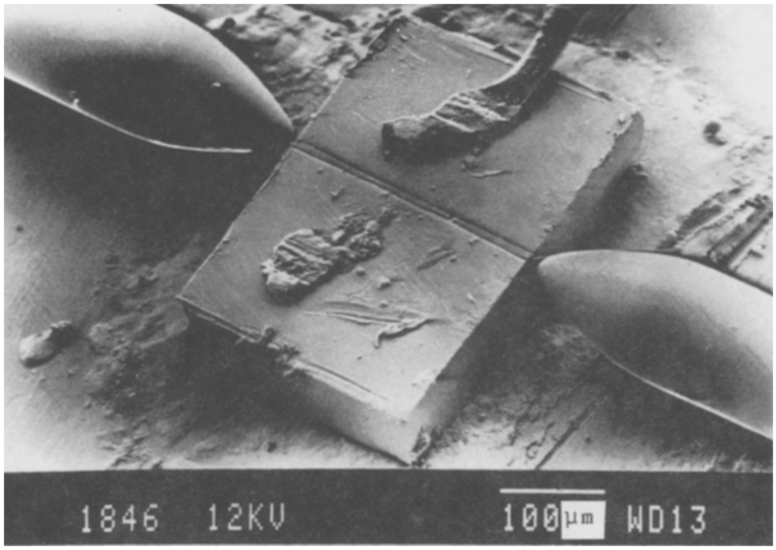

Fig. 5. Laser diode coupledon both sides to single-mode lightguides.

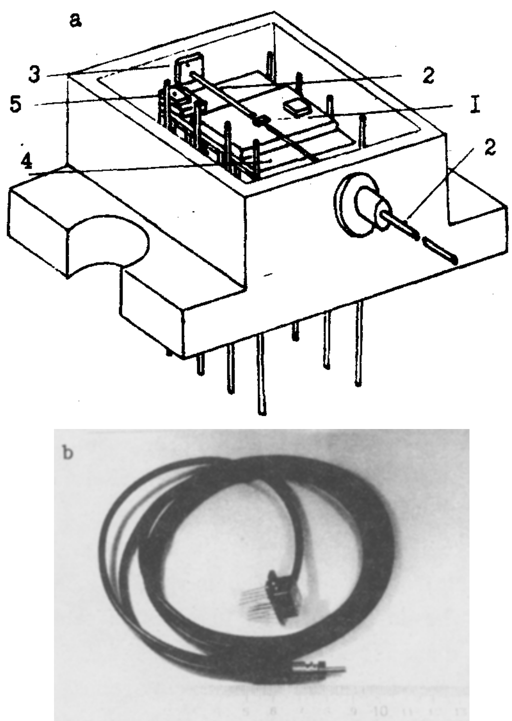

Fig. 6. Construction (a) and external vies (b) of LM-1300 optical-emitter module.

4. INFLUENCE OF EXTERNAL FEEDBACK ON THE MODULE OPERATION

Modules with "integral" coupling-in are not immune to the infuence of parasitic (uncontrollable) reflections of the laser emission, which take place both in the coupling unit and in the fiber channel, including reflections from the rather remote connectors. Such reflections lead to a number of undesirable effects such as occur in complex (composite) cavities or in lasers with external feedback. Both the presence of additional feedback and its instability with time cause excess noise of the laser emission in various frequency bands.

TABLE 3. Properties of Laser Modules

No.	Property	LM-1300	LM-1550
1.	Wavelength, μm	1.30 ± 0.06	1.55 ± 0.06
2.	CW emission wavelength in the fiber lightguide, mW, not less than	1	1
3.	Operating current, mA, not more than	80	100
4.	Threshold current, mA, not more than	45	65
5.	Maximum allowance current, mA	120	120
6.	Laser-diode voltage at 80 mA current, V	1.5-1.8	1.5-1.8
7.	Maximum modulation rate, Mbit/s	560	560
8.	Technical lifetime of emitting diode, h, more than	$5 \cdot 10^4$	$2 \cdot 10^4$
9.	Monitor photocurrent at 1 mW emission power, μA	50-100	50-100
10.	Microcooler maximum working current, mA	500	500
11.	Temperature-sensor working current, mA	10	10
12.	Temperature coefficient of sensor, mV/K	−2	−2

TABLE 4. Modules for 1.3 and 1.55 μm with Single-Mode Fiber-Optics Output Lead

Model	Composition		Note
	PD monitor	Peltier thermocouple and temperature sensor	
LM-1800, LM-1550	+	+	Intended for use in transmitters and repeaters with automatic control of the operating regime
LMF	+	–	Intended for laboratory testing apparatus
"E-2"	–	–	Intended for experimentation

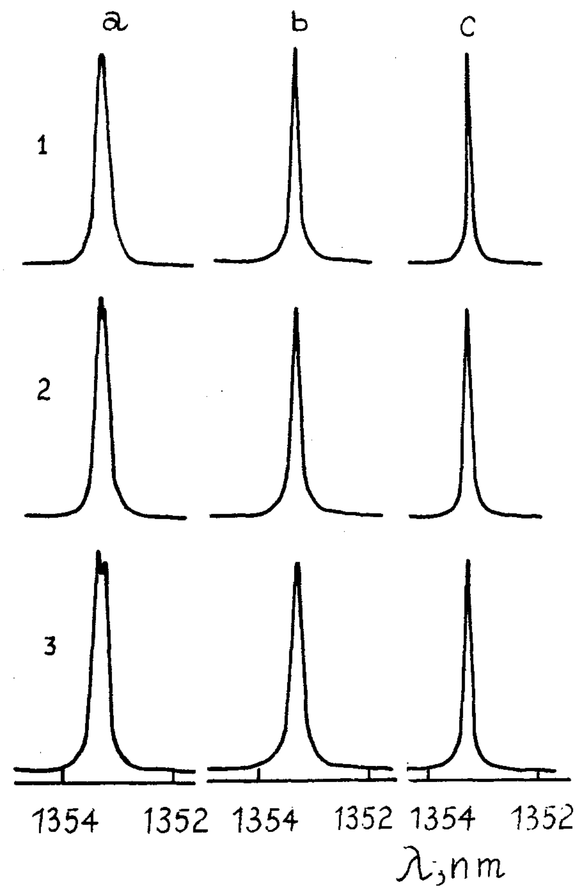

Fig. 7. Outline spectrum of optical emitter at certain values of the pump current: 60 mA (1), 70 mA (2), and 80 mA (3) – plane output face of the lightguide (a), microlense of radius $R = 60\ \mu$m (b), plane face tilted 10° to the lightguide axis (c).

Our present investigation has shown that the state of the end-face of the fiber-optics lead, located 0.5-1 m away from the face of the laser diode, exerts a definite influence on the operating regime of the laser in the module. This influence reduces to more or less known effects of external feedback, namely to modification of the emission spectrum (change of the spectral contrast in the single-frequency regime, efective broadening of individual spectral lines, the appearance of spectral satellites near the laser lines). This modification of the spectrum is qualitatively due to the development of automodulation pulsations at frequencies in the range 1-10 GHz, and the accompanying frequency "chirping," i.e., rapid drift of the frequency when the amplitude is varied (called also frequency modulation [12]). An interpretation of the broadening of the spectral modes was presented earlier in [13] and in a large number of later publications.

In one experiment performed with a single-frequency diode there was observed a clear-cut change of the spectral-line width when the shape of the free end face of the lightguide was changed. As can be seen from Fig. 7, if this end face is planar and perpendicular to the lightguide axis (curves *a*), the linewidith is a maximum. Narrowing of the spectrum causes fusion of the output end face of the lightguide (curves b) or tilting of the flat end relative to the axis (curves c). In both cases the feedback coefficient decreases, and is apparently lowest in the latter case, when the end face is tilted by approximately 10°. The linewidth is then decreased to one-half. Spectra plotted with the aid of a Fabry–Perot interferometer (resolution ~1 GHz) have shown, as seen from Fig. 8, that in the presence of parasitic feedback the laser-mode line has satellites. The frequency distance $\Delta\nu$ from the dominant line to the nearest symmetric satellite increases with increase of the pump current, as shown in Fig. 9, in the interval from 2 to 5 GHz, and the spectral width of the central line decreases from 4 GHz near the lasing threshold to 1 GHz at a current larger than 70 mA (the measured linewidth remains constant with further increase of the pump, since it agrees with the spectral resolution of the apparatus, ~1 GHz; at the same time, the actual lasing linewidth can be much smaller than this value). Thus, in this case the onset of self-modulation intensity oscillations (pulsations) firstly,

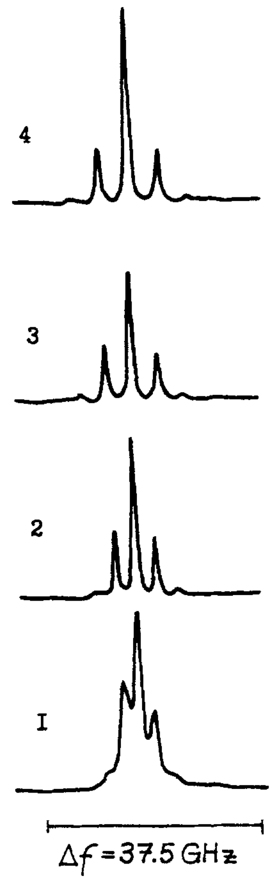

Fig. 8. High-resolution spectrum in the presence of parasitic feedback at a current 45 mA (1), 65 mA (2), 75 mA (3), and 85 mA (4).

does not shut off the single-frequency lasing, and secondly, is accompanied by the appearance of relatively narrow spectral satellites of the main line, as can be expected for the spectrum of an amplitude-modulated signal. This means apparently that in the pauses betwen the radiation pulses the intensity does not drop to the spontaneous-emission level, for otherwise it would be difficult to maintain a single-frequency regime in the averaged spectrum. Indeed, in the case of deep intensity modulation new coherent-radiation pulses are generated by the spontaneous background and turning-on many modes that are close (in Q and in gain) to the dominant mode become more probable. The fact that combination satellites have a small width is evidence of regularity of the self-modulation pulsations at the frequency $\Delta\nu$. If their frequency were not stable, this would be reflected in the satellite broadening. The satellites in Fig. 9 have approximately the same width as the dominant line. Thus, the relative rms deviation of the pulsation frequency at, say, ~4 GHz (70 mA current) is limited to 25%, and possibly less (the linewidth is less than 1 GHz). The noticeable narrowing of the dominant line when the current is increased from 40 to 70 mA can be interpreted as a natural Schawlow–Townes spectral narrowing, so that the excessive broadening as a result of "chirping" is not substantial, the presence of pulsations notwithstanding. This attests also to their small depth. As to the first-order satellites (at double the difference frequency, $2\Delta\nu$), their appearance can be attributed either to anharmonicity of the amplitude oscillations, or to an admixture of phase modulation. Note that these conclusions can be drawn from observation of high-resolution spectra, whereas outline spectra obtained with a monochromator might lead to an incorrect conclusion of a strong "chirping" of the laser frequency.

Superposition of a microwave pump-current component at 2 GHz did not change the single-frequency regime (see Fig. 10), i.e., the so-called dynamic single-frequency regime was obtained, with corresponding combination satellites appearing in the optical high-resolution spectrum (up to 4 harmonics at the difference frequency 16 GHz). It can be seen that the satellite amplitudes are comparable with the central mode at the lower pumping (50 mA) and decrease with increase of the pump (to 85 mA). The reason is that the regime with a constant bias 50 mA corresponds to resonance of the external frequency with

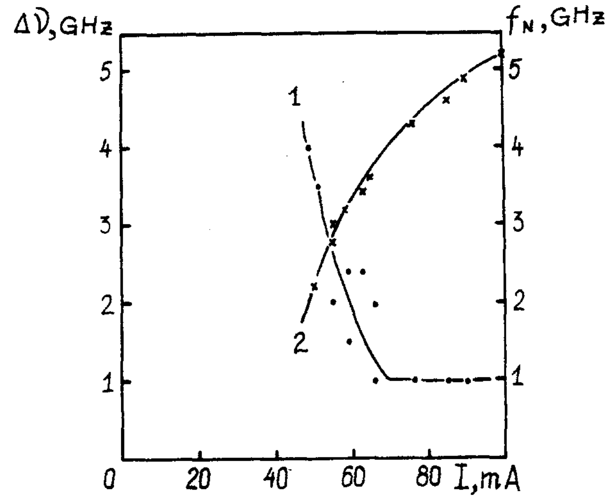

Fig. 9. Dependence of the linewidth (1) and of the noise-resonance frequency (2) on the pump current (in the presence of parasitic feedback).

the self-modulation frequency. The modulation depth is in this case maximal, a fact evidenced by the larger amplitude of the satellites. When the constant bias is increased, the resonance is upset, since the self-modulation frequency increases to ~5 GHz. It is this which leads to a certain decrease of the modulation depth, although in principle the inertia of the laser emitter is decreaed by the shortening of the effective lifetime of the excess carriers.

It follows from these results that laser sources of the type considered are suitable for modulation in a wide frequency band (at least up to 2 GHz), and the frequency of the relaxation resonance is 2-5 GHz and rises regularly with increase of the pump current. In the quasiresonance region there can occur self-modulation pulsations due to parasitic reflection from the output face of the fiber lead of the module. If, however, this reflection is eliminated, the self-modulation is substantially suppressed.

5. MOCK-UP TESTING OF INFORMATION TRANSMISSION

The experiments on information transmission were carried out with the laser-module sources using a mock-up of a single-mode fiber-optics system with an optical path up to 30 km long. We used a CMI code with a linear transmission rate 280 Mbit/sec. The receiver was a pin-photodiode based on Ge, with a sensitivity 30 dBm. We measured the relative (bit) error rate (BER) indicative of the quality of digital signal transmission. The background (instrumental) BER was $\leq 10^{-12}$.

We measured in one experiment the BER at transmission distances 15, 25, and 30 km. The channel included segments of a single-lead optical cable with a lightguide based on SiO_2, with light-transmitting core diameter 10 ± 2 μm. The first two segments, with a total length 15 km, had an average loss (including the conector losses) equal to 0.76 dB/km. The next 15 km of the cable had an average loss 1.33 dB/km. As indicated above, the transmitter was a laser module with a single-mode output operating at a wavelength 1300 nm. The threshold current J_t was 40 mA, and at a current of 60 mA one longitudinal mode predominated in the cw lasing spectrum. The operating regime of the laser corresponded to a constant bias at a level $0.86J_t$ on which information current pulses of 1.5-nsec duration were superimposed. The optical transmitter power fed to the cable was 1 mW.

The measurements have shown that at a transmission distance 15 km the BER remained within the background level, i.e., the error probability was less than 10^{-12}. This transmission quality is acceptable for most purpose, including communication between computers. The BER increased with further increase of the distance, as seen from Table 5. It can be found by interpolation from these data that the BER level $<10^{-9}$, which meets the usual requirements in communication applications, is reached up to a distance 27 km for the indicated characteristics, which are not optimal, of the optical channel and of the photoreceiver.

We have thus obtained in the experiment described above estimates of the quality of laser communication (in the regime of intensity modulation and direct detection), using the developed module sources in th 1300-nm band at a transmission rate 280 Mbit/sec in a mock-up of an ordinary cable optical channel. We have shown that a high communication quality

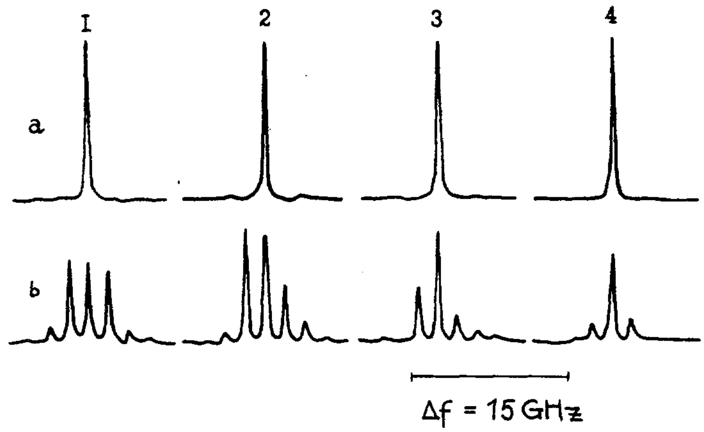

Fig. 10. High-resolution spectrum (a) in the case of feedback suppressed by tilting the output end face and modulated-signal spectrum (b), for several values of the pump current: 50 mA (a), 65 mA (2), 70 mA (3), and 85 mA (4).

TABLE 5. Results of Measuring the Error Probability with an Optical-Channel Mock-Up

Optical channel length, km		I5	25	30
Optical-signal power at receiver, dBm		-II,5	-I7,5	-3I,5
Measured error probability	(BER)	10^{-12}	3.10^{-10}	7.10^{-9}

(error probability not larger than 10^{-12}) is readily attainable at distances up to 15 km, and a BER level acceptable for usual applications (not more than 10^{-9}) can be obtained for a distance of 27 km.

CONCLUSION

Laser modules with active elements comprising injection-laser diodes based on buried InGaAsP/InP heterostructures have been developed. A distinctive feature of these modules is the use of single-mode lasers and fiber-optics leads. We used a precision microlens matching of these elements, which made it possible to obtain a laser-radiation input into a single-mode fiber track with an efficiency 50-60%. The module contains also a Peltier element, a temperature sensor, and a photodiode. We have investigated the power, spectral, and modulation characteristics of the emitters and have shown that they are suitable for use in system of long-distance fiber-optics communication.

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