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Simple and Effective Modulation of Diode Lasers

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Abstract—We demonstrate a simple and effective method of a multiple-frequency operation of diode laser by using the direct RF modulation of injection current. A substantial fraction of the total laser power (up to 40%) was obtained in a single side band at frequency range from 2.5 GHz to 4 GHz with microwave power less than 26 mW. We have found simple explanation of the high efficiency of modulation of the laser radiation spectrum based on resonant excitation of a relaxation oscillation.

1. INTRODUCTION

Diode lasers have recently found wide application in various fields of modern physics, such as spectroscopy, metrology, and atomic physics. Because of their small size, low cost, and high spectral characteristics, the use of such lasers has substantially simplified the conduct of experiments on atomic optics and laser cooling of atoms. When working with alkali metals featuring a hyperfine splitting of their ground state, of principal importance is the use of a two-frequency laser radiation. In that case, radiation at one of the frequencies exerts a force action on the atom in hand by exciting it from one of the hyperfine-structure sublevels of the lower state, while radiation at the other frequency provides for a cyclic character of the interaction between the atom and the laser field. The frequencies of both lasers here must be sufficiently stable in time in order that radiation should be in resonance with the appropriate transitions and the frequency difference be equal to the hyperfine splitting of the ground state of the atom (approx. 3 GHz for ^{85}Rb, 6.8 GHz for ^{87}Rb, and 9 GHz for ^{133}Cs). Note a number of concrete applications of a two-frequency field with a frequency difference corresponding to the hyperfine splitting of atoms: magneto-optical traps for alkali metals [1, 2], excitation of Raman transitions in atomic clocks [3], Raman velocity selection of atoms [4], and experiment on the exact measurement of the $\hbar/M$ ratio [5]. The use of two lasers with they separate optical and electronic systems materially complicates the experiment, and to stabilize the difference frequency of the lasers, it is necessary to make use of a special high-frequency electronic system [6]. An alternative method to produce a two-frequency laser radiation is to use an RF field: electro-optical modulation of the radiation, high-frequency acousto-optical modulation [7], direct RF modulation of the injection current of diode lasers with an external cavity [8, 9], RF modulation of the injection current in a single-frequency free-running mode [10], and phase-locked microwave frequency modulation in optically-pumped laser diodes [11]. A high modulation level in the GHz-frequency region can also be attained with the aid of noncoherent optical feedback [12].

Despite the fact that the methods to produce two-frequency laser fields are numerous, each of them features certain shortcomings that make the experiment either difficult to perform or costly. Light modulation requires the use of electro-optical and acousto-optical modulators that cost more than the laser diodes themselves, as well as powerful RF radiation sources. The use of direct RF modulation of the injection current of the free running diodes resulted in a low modulation index, and in the case of diodes in an external cavity, in a reduced output power [8].

It is believed that the use of optical feedback makes the lasers more useful in many applications, for example, in atomic physics [13]. However, the development of semiconductor laser technology has lead to the appearance in the commercial laser market of laser diodes possessing high spectral characteristics in single-frequency operation and continuous frequency tuning capabilities. Lasers using no optical feedback have a higher power output, and in some applications, the fact that they feature a greater line width is preferable (e.g., in the work reported in [14] special methods were used to broaden the line width of a semiconductor laser in order to effectively cool a beam of caesium atoms).

In this paper, we report on an effective method to achieve two- and multiple-frequency lasing in free-running diode lasers with a frequency difference corresponding to the hyperfine splitting of ^{85}Rb atoms by means of direct RF modulation of the diode current. This method enables one to obtain, in a simple and cheap way, a multiple-frequency laser radiation with a fixed frequency difference for various modes that is needed in many applications. The high-frequency mod-

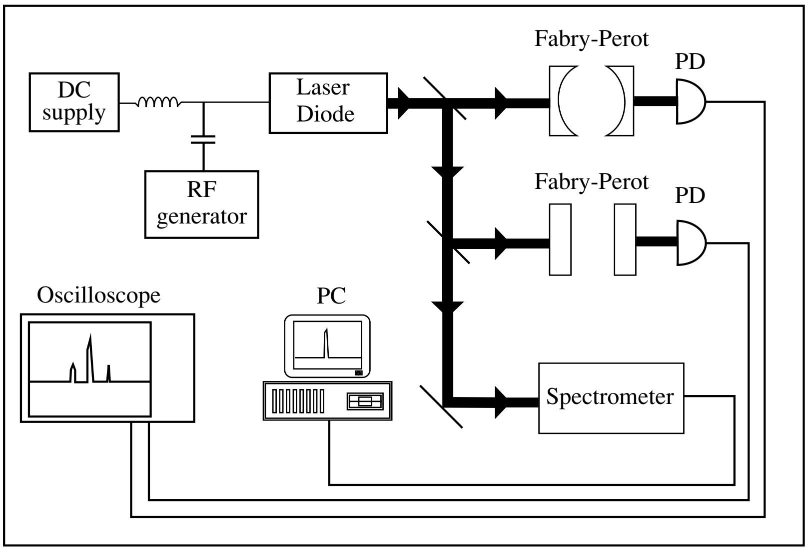

Fig. 1. Schematic diagram of the experimental setup used to study the direct RF modulation of diode lasers.

ulation of semiconductor lasers is being widely used in optical data transmission systems. For example, the authors of [15] successfully demonstrated modulation in the range 0.2–17 GHz in heteroepitaxial-ridge-overgrown distributed feedback lasers. However, in the field of atomic physics such lasers have found no wide application. We have managed to realize a diode current modulation regime wherein a sizeable proportion of the total laser power is in side bands. Our method envisages no resort to special skills in microwave techniques, and efficient modulation is achieved with a low-power RF radiation source.

The paper is organized as follows. Section 2 gives a description of the experimental setup used to investigate the RF modulation of diode laser injection current. In Section 3, we present the brief introduction to the theory of frequency and amplitude modulation spectra of optical signals. In Section 4 experimental results are described and the explanation of the high efficiency of modulation of the laser radiation spectrum is suggested.

2. EXPERIMENTAL SETUP

The experimental setup to study the RF modulation of a diode laser radiation is shown schematically in Fig. 1. In our experiments, we have used commercially available laser diodes Model HL7851G (Hitachi) with a maximum power output of 50 mW and a wavelength of 784.7 nm at 25°C. The threshold laser current is equal to 46.8 mA. Microwave radiation was coupled into the diode by means of a 60 cm long coaxial cable whose one end was fixed to the diode pins (the pins were shortened to 1 cm) and the other, via a 1-pF capacitor, to a microwave source with a power output up to 26 mW. To decouple the RF source from the d.c. source of the diode laser, the latter was connected to the diode via an inductance coil. We took no special measures to match the impedances of the coaxial cable and the laser diode. Using the laser diode radiation spectra obtained we found that the diode received around 50% of the RF radiation power coupled into it.

The laser radiation spectrum was analyzed with the aid of a spectrometer and a plane and a spherical Fabry–Perot etalons. The plane Fabry–Perot etalon had a free spectral region of $\Delta\nu_p = 18$ GHz and a resolution of $\delta\nu_p = 900$ MHz, and the spherical etalon, $\Delta\nu_s = 2$ GHz and $\delta\nu_s = 10$ MHz, respectively. The resolution of the spectrometer was 3 GHz, and the radiation spectrum at its output was registered by means of a CCD allowing a spectral region of 34 nun to be displayed on a monitor screen.

3. RADIATION SPECTRUM IN THE CASE OF DIRECT CURRENT MODULATION

Consider the spectral characteristics of a laser whose injection current has, in addition to a D.C. component I_0, also a component oscillating with a frequency of ω_m, i.e., $I = I_0 + i_m \sin(\omega_m t)$. The output power of a laser diode depends on its injection current, and so such a modulation of the diode current results in the modulation of the power output of the laser. Since the refractive index of the active medium of the laser diode and its cavity length depend on the diode current, there takes place both the amplitude and frequency modulation of the laser radiation spectrum.

A frequency-modulated optical wave is described by the expression

$$E = E_0 \exp[j(\omega_0 t + \beta \sin(\omega_m t))], \tag{1}$$

$$\beta = 2\pi\Delta F/\omega_m, \tag{2}$$

where ω_0 is the laser radiation frequency, ΔF is the maximum frequency deviation, and β is the modulation index. The result of such a modulation is the appearance in the frequency spectrum of the laser radiation of side bands on the left and right of the radiation line ω_0 at distances that are multiples of ω_m.

The spectrum of the frequency-modulated wave is defined by the expansion of Eq. (1) into a Fourier series and is expressed in terms of the first-order Bessel function $J_l(\beta)$:

$$E = J_0(\beta)E_0\sin(\omega_0 t) + J_1(\beta)E_0\sin((\omega_0 - \omega_m)t) - J_1(\beta)E_0\sin((\omega_0 - \omega_m)t) + \ldots + J_l(\beta)E_0 \times \sin((\omega_0 + l\omega_m)t) + (-1)^l J_l(\beta)E_0\sin((\omega_0 - l\omega_m)t). \quad (3)$$

The squares of the coefficients of the sines in Eq. (3) determine the intensities in the corresponding side bands of the radiation spectrum.

The amplitude modulation of the laser diode radiation manifests itself in the asymmetry the laser radiation spectrum: the intensities in the nth and $-n$th side bands do not coincide. A frequency- and amplitude-modulated optical wave is described by the expression

$$E = E_0[1 + M\cos(\omega_m t)]\exp[j(\omega_0 t + \beta\sin(\omega_m t))], \quad (4)$$

where M is the degree of modulation. The Fourier-series expansion of Eq. (4) yields the following expression for the amplitude at the fundamental frequency:

$$J_0(\beta)E_0, \quad (5)$$

the amplitudes in the first and minus first side bands being respectively given by

$$[J_1(\beta) + (M/2)\{J_2(\beta) + J_0(\beta)\}]E_0, \quad (6)$$

$$[-J_1(\beta) + (M/2)\{J_2(\beta) + J_0(\beta)\}]E_0. \quad (7)$$

Thus, in the case of simultaneous amplitude and frequency modulation of the wave, the amplitude of the first side band differs from that of its minus first counterpart. Expressions (6) and (7) also show that the modulation index β can be obtained from the average amplitudes of the first and minus first side bands, and the degree of modulation, from their difference.

4. EXPERIMENTAL RESULTS

The characteristic spectra of a Model HL7851G (Hitachi) laser diode with the frequency modulation of the injection current, obtained with the aid of a scanning plane Fabry–Perot etalon, are presented in the left-hand column of Fig. 2. This series of spectra was obtained at various powers of the microwave field and an injection current modulation frequency of f_m = 3 GHz. Figure 2a shows the radiation spectrum of the laser with the microwave field switched off, and Figs. 2b through 2d, the spectra of the laser with progressively increasing microwave field power. It can be seen from the figures that in the presence of the RF field there appear side bands on the left and right of the carrier frequency at distances that are multiples of f_m. As the RF field power is increased, the radiation power at side frequencies grows higher, while that at the carrier frequency decreases. The spectrum shown in Fig, 2d was obtained at a microwave field power of 26 mW. At this value of an RF field power there takes place the excitation of the third-order side bands, and the radiation power in the first side band is several times that at the carrier frequency. Moreover, there can be seen a weak amplitude modulation of the radiation spectrum: the signal intensities in the nth and $-n$th side bands are not the same. The right-hand column of Fig. 2 presents the spectra obtained by fitting Eq. (4) on to the experimental results given in the left-hand column with the modulation index β and the degree of modulation M as fitting parameters. One can see from Fig. 2 that Eq. (4) yields values which agree with the experimental results accurate to within 10%.

We studied the relationship between the modulation index of the laser radiation and the injection current at a fixed microwave power. We took the ratio $\gamma = I_1/I_0$ between the first-side-band and carrier-frequency radiation intensities to serve as a measure of the modulation index. Such a definition is convenient for practical applications. In our experiments, the intensity of the second-order side band never exceeded that of the first-order side band, and so an increase of the modulation parameter γ introduced by us corresponds to an increase of the generally accepted modulation index β described above (in the general case, when the modulation index β is so high that the intensity of the first side band is equal to zero, the modulation parameter γ goes to zero and thus loses physical meaning). The experimental results obtained are presented in Fig. 3. As can be seen, the above relationship is obviously of resonance character. At an injection current of 65 mA the modulation index reaches its maximum, the parameter γ being equal to 3.2 at an RF power of P = 26 mW; hence, the intensity in a single side band equals 40% of the total laser power.

We could not find any description of such resonance behavior in the literature devoted to the modulation of the radiation of diode lasers. The authors of [8–10] noted that the intensity of the side bands of the modulated radiation of a diode laser increased as its injection current was reduced, but failed to notice any subsequent decrease of the modulation index. The increase of the modulation index of the radiation with the decreasing injection current of the laser was explained by an increase of the modulation index of the current. Indeed, as the dc component of the current I_0 is reduced with i_m remaining unchanged (because of the fixed RF power coupled in), the modulation index i_m/I_0 of the injection current increases, leading to an increase of the modulation index β. The modulation index of the radiation spectrum, i.e., the ratio between the squares of the coefficients of the appropriate terms in Eq. (3), is a

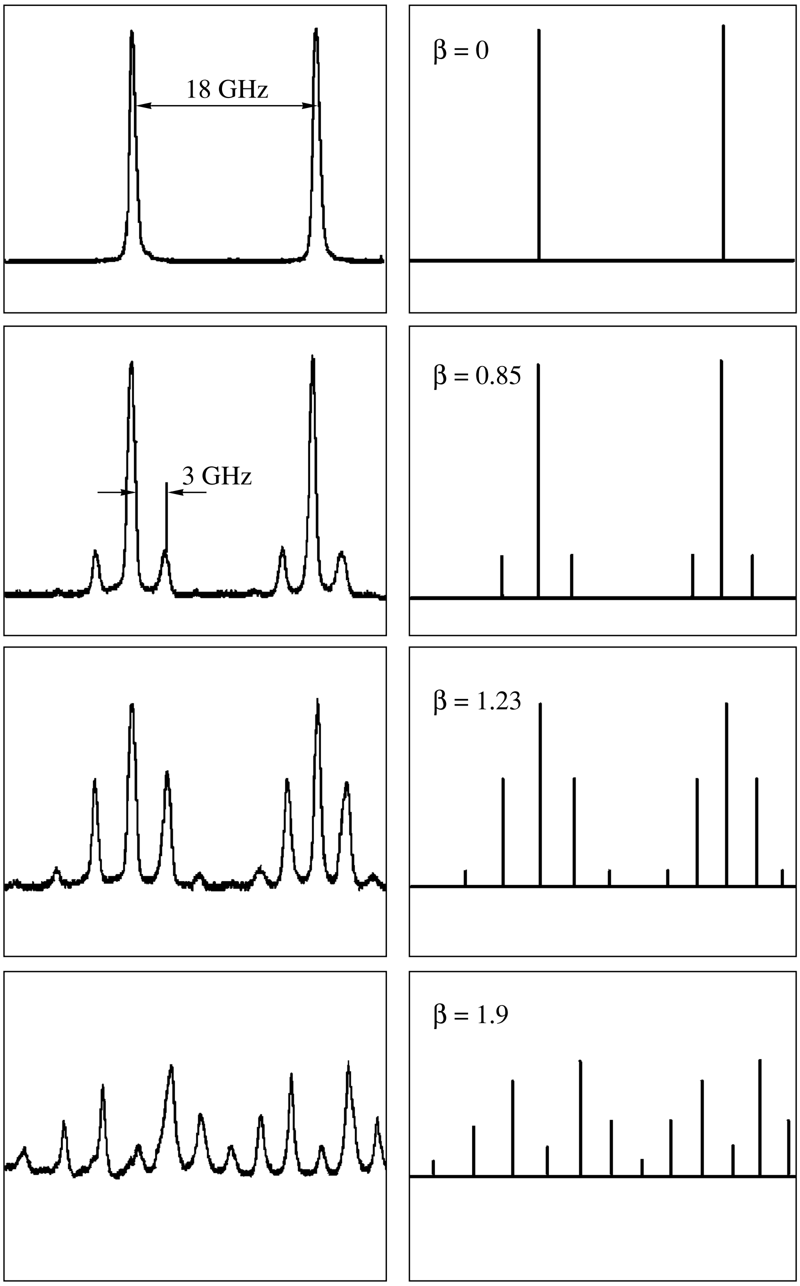

Fig. 2. Radiation spectra of a diode laser with microwave modulation of the injection current. Left-hand column presents experimental results; right-hand column shows the corresponding theoretical curves. (*a*) diode laser radiation spectrum in the absence of modulation of the injection current; (*b*) through (*d*) spectra obtained with progressively increasing modulation index of the injection current.

monotonically increasing function (within the considered interval of β), and so it is difficult to explain within the framework of the model suggested the reduction of the modulation index of the radiation spectrum with further decrease of the injection current.

We think that the behavior of the modulation index found by us is due to the dependence of the relaxation oscillation frequency of the diode laser on its injection current. At some value of the injection current, the frequency of relaxation oscillations coincides with the frequency of the microwave field, and this causes the modulation index to rise. At other injection current values the frequency of relaxation oscillations fails to coincide with that of the RF field, oscillations are excited only in part, and the greater the frequency difference, the lower the modulation index of the radiation spectrum. The validity of the physical model suggested can be verified as follows.

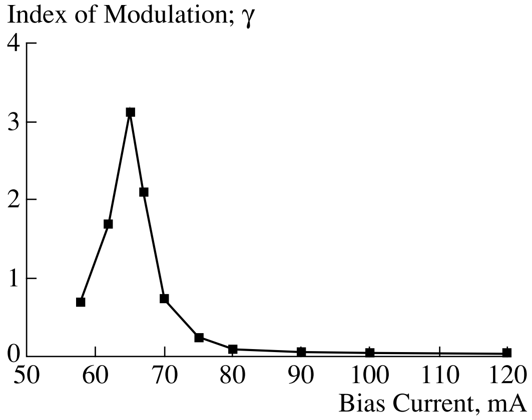

Fig. 3. Modulation index of the laser radiation (ratio between the radiation intensities in the first side band and that at the fundamental frequency) as a function of the injection current modulated at a frequency of 3 GHz (RF power 26 mW).

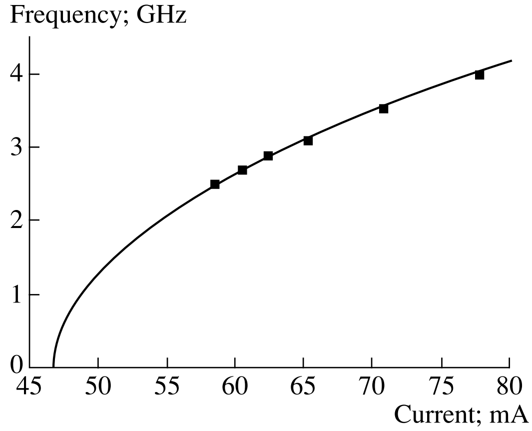

Fig. 4. Relaxation oscillation frequency of a diode laser as a function of the injection current. The solid line depicts the theoretical relationship. The data points correspond to experimental measurements.

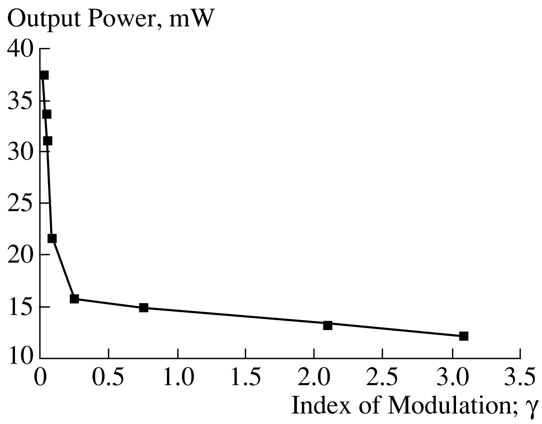

Fig. 5. Relationship between the radiation power of a diode laser and the modulation parameter γ.

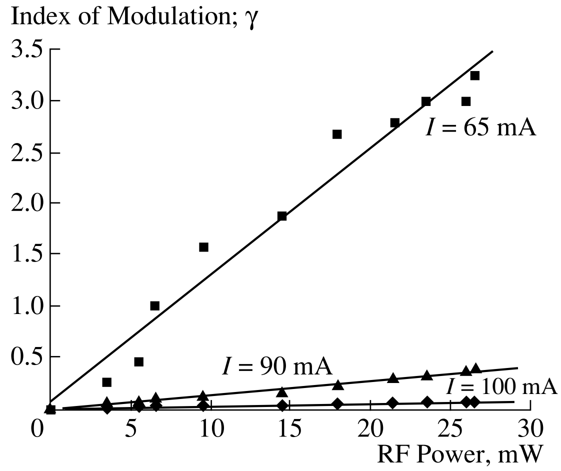

Fig. 6. Modulation index of the radiation of a diode laser as a function of the power of the RF field at various injection current values.

The injection current dependence of the relaxation oscillation frequency is defined by the following expression [16]:

$$f_r = K\sqrt{I/I_{th} - 1}, \tag{8}$$

where the coefficient $K = \sqrt{\dfrac{1}{\tau_s \tau_{ph}}}$, τ_s is the lifetime of the carriers, and τ_{ph} is the effective lifetime of photons in the cavity.

We experimentally determined the injection current values corresponding to the maximum modulation index of the laser radiation spectrum at various frequencies of the RF field (in range of our RF generator from 2.5 GHz to 4 GHz). The data points thus obtained are depicted by squares in Fig. 4. The solid line in Fig. 4 shows dependence (8) with the coefficient K obtained by fitting by the chi-square criterion expression (8) to the experimental data points. This coefficient proved to be equal to 4.9 GHz, which also corresponds to the data presented in [17], where the coefficient K ranged between 3.0 and 5.3 GHz. Note we have not that experimental data points at the injection current near I_{th}. Thus, the physical model suggested describes well enough the operation of diode lasers with RF modulation and allows their basic constant to be found.

An important characteristic of a diode laser is its output radiation power. Our measurements showed that high modulation indices were obtained with small injection currents, hence with lower output radiation powers. Figure 5 presents the output power of a laser as a function of the modulation index of its radiation spectrum. It can be seen that frequency modulation at which the intensity in the first side band amounts to 10% of the intensity at the fundamental frequency can easily be achieved at a total laser power of 25 mW. To attain a higher radiation power at a given modulation index, it is necessary to increase the power of the RF filed (note that frequency modulation with a 10-percent power in the first side band is more than sufficient in many an application).

The relationship found by us between the modulation index and the RF field frequency at various injection current values is presented in Fig. 6. In the variation interval of the RF power studied, the modulation index increases linearly with increasing RF power. The closer the injection current of the laser to its resonance value (65 mA in our case), the stronger the dependence of the modulation index on the RF power, and accordingly, the easier it is to achieve frequency modulation in a diode laser at a moderate power of the RF field.

The radiation wavelength of a free-running diode laser is known to depend on both its current and temperature. We also studied the relationship between the modulation index of the radiation of a diode laser and its temperature. Our measurements showed that at temperatures in the range 4–10°C and fixed diode current values the ratio of the radiation intensity in the first side band to that at the carrier frequency (the modulation parameter γ) varied by no more than 25%. Thus, a high modulation index of the radiation of a diode laser can be achieved at various laser diode temperatures, hence at various wavelengths.

5. CONCLUSION

Using the direct RF modulation of the injection current of a diode laser, a multiple-frequency lasing mode is attained in this work, with controllable frequency difference between the radiation spectrum modes and ratio between the radiation intensities in them. A physical model based on the excitation of the relaxation oscillations is used to explain the high efficiency of modulation of the laser radiation spectrum. The method studied for attaining modulation of diode laser radiation is simple and requires no special RF techniques or devices.

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