Optica Applicata VIII/2, 1978

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Lasers and their application in optoelectronics

The applicability of lasers in various branches of optoelectronics is discussed. The special attention being given to the tuning mechanisms and methods.

Optoelectronics is usually considered as a interdisciplinary field joining optics and electronics, as it applies optical as well as electronical methods to solve some problems. With the advent of lasers it obtained new and wide possibilities for further development taking advantage of such phenomena as interference, optical mixing and ultrashort impulses. At present optoelectronics stimulates the development of other branches of science and technology, e.g. integrated optics, thin film optics, communication at optical frequencies, optical computers etc.

The following basic areas of optoelectronics may be actually distinguished:

a) optical sources of radiation (coherent and spontaneous),

b) passive elements (beam splitters, attenuatores, prisms, gratings, fibres, etc.),

c) active elements (modulators, beam deflectors),

d) detectors (photomultipliers, photodiodes, photoresistors, etc.).

In this paper the coherent radiation sources, especially their development during last years, and their application in laser Doppler velocimetry will be discussed.

In spite of the fact that semiconductor lasers have a firm position in optoelectronics, due to their compactness, spectral brightness and suitable spectral range an intense effort has been recently devoted to the development of tunable lasers. These lasers offer new possibilities in different fields of science and technology. Stimulated emission with broadly tunable wavelength range can be generated using some of the mechanisms specified below, depending on the characteristics of active medium and chosen spectral range.

a) Level tuning — this mechanisms is schematically represented in fig. 1a. The energy gap between the upper and lower laser levels can be roughly changed by impurities, and fine frequency adjustment can be done by some external influence, e.g. temperature, pressure, magnetic field. This concept is realized in tunable semiconductor laser. For details we refer to [1].

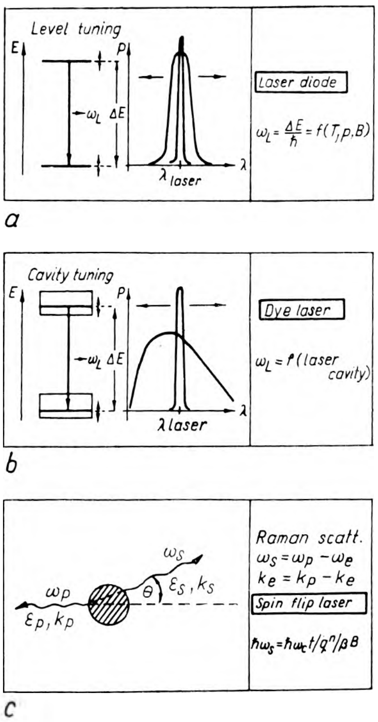

Fig. 1. a) Level tuning, b) cavity tuning, c) Raman scattering

b) Cavity tuning — the stimulated emission was initially belived to be obtainable only in media with narrow gain bandwidth. Broadband media were neglected. If, however, broadband emission is obtained, then the laser line can be in some way shifted within the emission band. This is the case of the laser based on organic molecules (fig. 1b). The wavelength is determined by a wavelength-selective feedback in the cavity.

c) Raman scattering — it provides another tuning mechanism especially in the infrared region (fig. 1c). In this case a pump photon of frequency ω_p is scattered inelastically by a medium at the angle Θ. The

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scattered radiation has a frequency ω_s, determined by the energy conservation condition. In order to obtain tunable radiation it is necessary to find a medium with elementary excitation whose frequency ω_e can be easily changed. The spin-flip Raman process involves excitation during which the spin of a conduction electron is reserved with respect to the external magnetic field, and therefore it represents a suitable scattering medium. The energy conservation rule is

$$\hbar\omega_s = \hbar\omega_p \pm |g|\,\beta B \tag{1}$$

where β — Bohr magneton, g — g-factor, B — induction of external magnetic field.

Let us notice that there exist also another possible methods of tuning (even if not widely used) and that the frequency tuning can be broadly widened by applying the methods on non-linear optics.

We shall discuss in detail the case of cavity tuning of organic dyes lasers whose physical properties have been reported recently in other papers [2]. The possible tuning methods are the following:

a) Tuning by a diffraction grating — introducing an element inside the dye laser cavity so that its

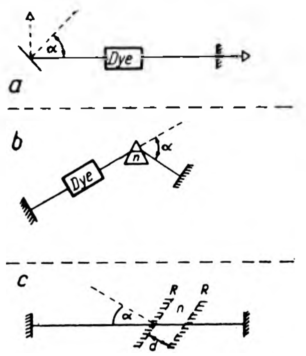

Fig. 2. a) Diffraction grating, b) prism, c) Fabry–Perot

reflectivity is a function of wavelength the operating wavelength can be controlled and tuned within the broad emission profile. The simplest dispersion element is the diffraction grating which replaces one of the mirrors (fig. 2a). The angular dispersion of the grating is governed by the relation

$$\frac{d\alpha}{d\lambda} = \frac{m}{2d}\,\frac{1}{\cos\alpha}, \tag{2}$$

where m — order of the reflection, d — groove spacing, α — angle of incidence. The bandwidth of the generated radiation will be given by the wavelength within the beam divergence ($\Delta\Theta$)

$$\Delta\lambda_{gn} = \frac{2d}{m}\cos\alpha\Delta\Theta. \tag{3}$$

Assuming the following experimental data for the R6G laser

$$\Delta\Theta = 5\ \text{mrad},\ d = 2100/\text{mm},\ m = 1,$$

we obtain from eq. (3) the bandwidth $\Delta\lambda = 4.6$ nm, e.g. the bandwidth more than one order larger than that of ordinary gas lasers. The losses introduced into the system by the grating are large, therefore this method is suitable only for high gain systems.

b) Tuning by a prism; it represents an alternative to diffraction grating (fig. 2b). In this case the losses introduced are negligeable, and the angular dispersion is given by

$$\frac{d\alpha}{d\lambda} = \frac{d\alpha}{dn}\,\frac{dn}{d\lambda}. \tag{4}$$

Using the prism at Brewster angle the bandwidth is given by

$$\Delta\lambda_p = \frac{\Delta\Theta}{4}\,\frac{dn}{d\lambda}.$$

For prism of high optical quality (i.e. for SF 18 $(dn)/(d\lambda) = 10^3$) we may obtain $\Delta\lambda = 1$ nm. Owing to small losses this method is suitable for *cw* systems

c) Very narrow bandwidth can be obtained using the Fabry-Perot etalon (fig. 2c), its angular dispersion is given by

$$\frac{d\lambda}{d\alpha} = \frac{2nd}{m}\sin\alpha, \tag{5}$$

and the bandwidth is

$$\Delta\lambda_{et} = \frac{2nd}{m}\sin\alpha\Delta\Theta. \tag{6}$$

This indicates that the bandwidth is strongly dependent on the angle of incidence α. In the limit $\alpha \to 0$ the bandwidth is determined by the etalon finessee and is given by a simple formula

$$|\Delta\Theta|_{\alpha\to 0} = \frac{\Delta\lambda}{F}, \tag{7}$$

where $F = \pi R^{1/2}\,(1-R)^{-1}$ and R is the reflectivity. For $\Delta\lambda = 5$ nm, $F = 300$ (for $R = 0.99$) the bandwidth $\Delta\Theta = 0.016$ nm, thus it is comparable with that of gas lasers. For the angle of incidence $\alpha > 0$ the bandwidth becomes limited by beam divergence. In the above example this occurs for $\alpha \geqslant 7$ mrad.

d) The distributed feedback systems are another important class of tuning elements in which the possibility of producing the grating within the active medium itself is exploited rather than using an external grating. Such a distributed grating can be produced by interfering two pumping laser beams and thereby producing a gain modulation. Referring to fig. 3a we may write the index of refraction

$$n(z) = n_0 + n_1 \cos kz. \quad (8)$$

The passive bandwidth may be expressed as

$$(\Delta\lambda)_{\text{feed}} = \frac{\lambda_0^2}{4\pi nL} \ln G. \quad (9)$$

For typical values $(G \sim 100)\, \Delta\lambda = 0.01$ nm.

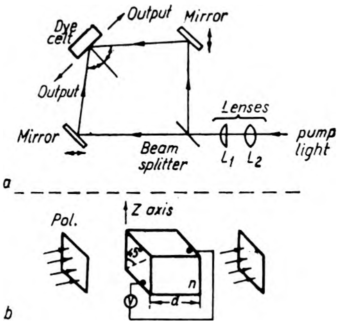

Fig. 3. a) Distributed feedback, b) birefringence filter

e) All the tuning methods discussed so far require mechanical control of the output wavelength, i.e. tuning is slow. The final possibility to be examined in our paper is the use of birefringent filter within the cavity, which allows a direct electronical control and, therefore, a very rapid tuning (fig. 3b). The filter consists of KDP crystal and two polarizers positioned at the angle of 45°. The transmission of such a filter can be expressed by

$$T = \cos^2\left(\pi d \frac{\Delta n}{\lambda}\right), \quad (10)$$

where d is crystal length, Δn is birefringence. The bandwidth is given by

$$\Delta\lambda_{\text{bf}} = \left(\frac{\lambda^2}{\pi} \Delta n d\right)(\Delta T)^{1/2}, \quad (11)$$

and is independent of the beam divergence. It depends, however, on how far above the treshold the laser is operated due to treshold dependence of T.

Assuming $\Delta T = 10\%$, $d = 2$ cm, $\lambda = 600$ nm we obtain bandwidth $\Delta\lambda_{\text{bf}} = 0.05$ nm, that is slightly worse compared with that obtainable with Fabry-Perot etalon. Let us notice that Δn may be changed by applying a voltage along the crystal axis.

Tunable lasers are already used in spectroscopy [3], air pollution measurements [4], holography and photochemistry.

In the following part of the paper laser Doppler velocimetry will be discussed as a special case of application of fixed-frequency laser in optoelectronics. Any optoelectronical system should consist of a source of radiation, an optical system for guiding the beam, a detector or receiver, and an appropriate electronics circuits for processing the obtained information.

The laser Doppler velocimeters measure the velocity of moving microscopic or macroscopic objects of different nature (e.g. solid, liquid, gaseous, areosol objects). The information is obtained at optical frequency and should be transformed somehow to radio-frequency region. We shall be particularly interested in the interaction of coherent electromagnetic wave with different objects, spectrum of scattered wave and its information contents as well as the spectrum analysis method. Let us consider that an object O moving with velocity v, much lower than the velocity of light c, is illuminated by linearly polarized plane wave

$$E_1(\boldsymbol{r}, t) = E_0 \exp i(\boldsymbol{k}_1 \boldsymbol{r} - \omega_0 t) \quad (12)$$

where E_0 — amplitude, $\boldsymbol{k}$ — wave vector, $\boldsymbol{r}$ — radius vector, ω_0 — angular frequency.

The intensity of the scattered wave will be

$$E_2(\boldsymbol{r}, t) = AE_0 \exp i[\boldsymbol{k}_2 \boldsymbol{r} - (\boldsymbol{k}_2 - \boldsymbol{k}_1)\boldsymbol{v}t - \omega_0 t]. \quad (13)$$

It is obvious that the frequency of scattered wave is shifted by

$$\Omega = (\boldsymbol{k}_2 - \boldsymbol{k}_1)\boldsymbol{v} \quad (14)$$

due to Doppler effect.

According to the Wiener–Khinchin theorem [5] the spectrum of the scattered plane wave can be calculated as the Fourier transformation of an autocorrelation function

$$S(\omega) = \operatorname{Re} \int_0^\infty R_E(\tau) \exp(-i\omega\tau)\, d\tau, \quad (15)$$

where

$$R_E(\tau) = \langle E(0) E^*(\tau) \rangle. \quad (16)$$

For the sake of simplificity let us assume that all scattering centra are similar. Then the spectrum for some typical values of velocity of scattering objects can be calculated as follows (table).

Velocity $\boldsymbol{v}$	Spectrum $S(\omega)$
0	$\delta(\omega - \omega_0)$
const $\neq 0$	$\delta(\omega - \omega_0 - \Omega)$
$\boldsymbol{v}_{A_v} + \boldsymbol{v}_{\text{dif}}$	$\dfrac{(\boldsymbol{k}_2 - \boldsymbol{k}_1)^2 D}{[(\boldsymbol{k}_2 - \boldsymbol{k}_1)^2 D]^2 + [\omega - (\boldsymbol{k}_2 - \boldsymbol{k}_1)\boldsymbol{v}_{A_v} - \omega_0]^2}$

The last case may serve as a simplified model of diffusion motion. The spectrum has then a Lorenz shape and is shifted due to the Doppler shift. The minimum value of speed detectable by laser Doppler velocimeters may be obtained from the condition, that the Doppler shift should be smaller than the half-width spectrum:

$$(\boldsymbol{k}_2-\boldsymbol{k}_1)^2 D < (\boldsymbol{k}_2-\boldsymbol{k}_1)\,\boldsymbol{v}. \tag{17}$$

Assuming $D = 10^{-12}\ \mathrm{m^2/s}$ (diffusion coefficient), $n = 1$, $\lambda = 6\cdot 10^{-7}$ m, $\sphericalangle(\boldsymbol{k}_2, \boldsymbol{k}_1) = 45°$ we obtain

$$v_{\min} = 10^{-5}\ \mathrm{m/s}.$$

At reasonable velocities, of the order of 1 m/s, the Doppler shift is approximately 1 MHz, i.e. relatively small if compared with optical frequencies. Its direct detection is not possible, so we have to look for some methods allowing its transformation into the radiofrequency range. This can be done using the method of non linear optical mixing at the non linear detector.

Let us assume that the scattered wave interferes with the reference one at the detector plane. The photocurrent is governed by square power rule

$$i(t) = c\cdot E_{TOT}^2, \tag{18}$$

where $E_{TOT} = E(t)+E_R(t)$ (the subscript R denotes the reference wave). The reference wave is the plane emitted by the laser

$$E_R(t) = A(t)\cos[\omega_0 t+\alpha(t)]. \tag{19}$$

The scattered wave is

$$E(t) = B(t)\cos\left[(\omega+\Omega)t+\alpha\left(t+\frac{\Delta s}{c}\right)+\Delta\alpha(t)\right], \tag{20}$$

where $\alpha(t)$ is time-dependent phase, Δs is the path difference of reference and scattered waves, $\Delta\alpha$ is fluctuations.

Applying the Wiener–Khinchin theorem we can calculate the photocurrent spectrum

$$I(\omega) = \mathrm{Re}\int_0^\infty \langle i(0)\,i(\tau)\rangle \exp(-i\omega\tau)\,d\tau, \tag{21}$$

where the autocorrelation function is defined as follows

$$\langle i(0)\,i(\tau)\rangle = C^2\langle[E_R(0)+E(0)]^2\,[E_R(\tau)+E(\tau)]^2\rangle. \tag{22}$$

Due to a randomness of fluctuations the number of terms in this expressions is reduced to five. Two of them represent the steady component, therefore the most important terms are:

1. $\langle E_R^2(0)E_R^2(\tau)\rangle$,

which represents interference mixing of reference wave with itself;

2. $\langle E^2(0)E^2(\tau)\rangle$,

which represents mixing of scattered wave with itself;

3. $\langle E_R(0)E_R(\tau)E(0)E(\tau)\rangle$,

which represents mixing of reference and scattered waves. Only this term carries the necessary information (e.g. the Doppler frequency).

Let us point out that all these considerations holds for single made as well as multimode lasers, provided that the mode separation is larger than the Doppler shift. From the experimental point of view the laser Doppler velocimeters differ mainly in the manner of obtaining the reference beam. Some typical arrangements are schematically shown in fig. 4, where a) is the arrangement with local oscillator for spectral and transparent objects, b) is so-called differential arrangement for spectral and transparent objects. In this case the detector is illuminated by scattered and references waves with the same wave vectors, c) is so-called symmetrical mixing. The detector is exposed to two waves with different wave vectors, d) is so-called wide angle Michelson velocity interferometer (WAMI), in which — contrary to the previous arrangements — a delayed scattered wave is used as a reference wave. This arrangement is especially useful for the measurements of high velocities (using the delay line, with $\tau_d = 6\cdot 10^{-9}$ s, $v_{\min} = 50$ m/s).

All previous formulae were derived by assuming coherent fields of scattered and reference waves on the photodetector. In general, these fields may be not fully coherent, as the scattering centra may be located arbitrarily in the space. Applying the Van Cittert–Zernike theorem [5] the maximum area of the detector can be calculated, depending on the distance from the scattering centra at which both the waves are coherent. This condition is fulfilled only for small-area detectors [6]. Let us point out that such a detector is also advantageous from the point of view of noise suppression. The differential arrangement is preferred as it shows the best signal: noise ratio. Usually, the noise is also suppresed if the interference filters are placed in front of the detector.

A laser Doppler velocity-meter based on the scheme with a local oscillator was realized at the Faculty of Nuclear Science and Physical Engineering, Czech Technical University Prague. Another laser, using the differential scheme was realized in the Institute of Instrumental Technique, Czechoslovak Academy of Sciences in Brno. We shall discuss the first one, intended for the measurements of velocities up to 10 m/s. An He–Ne laser with output power 3 mW, frequency separation of longitudinal modes 100 MHz and amplitude stabilization, was used as the radiation source (type ENV 3 Tesla). A photomultiplier Tesla

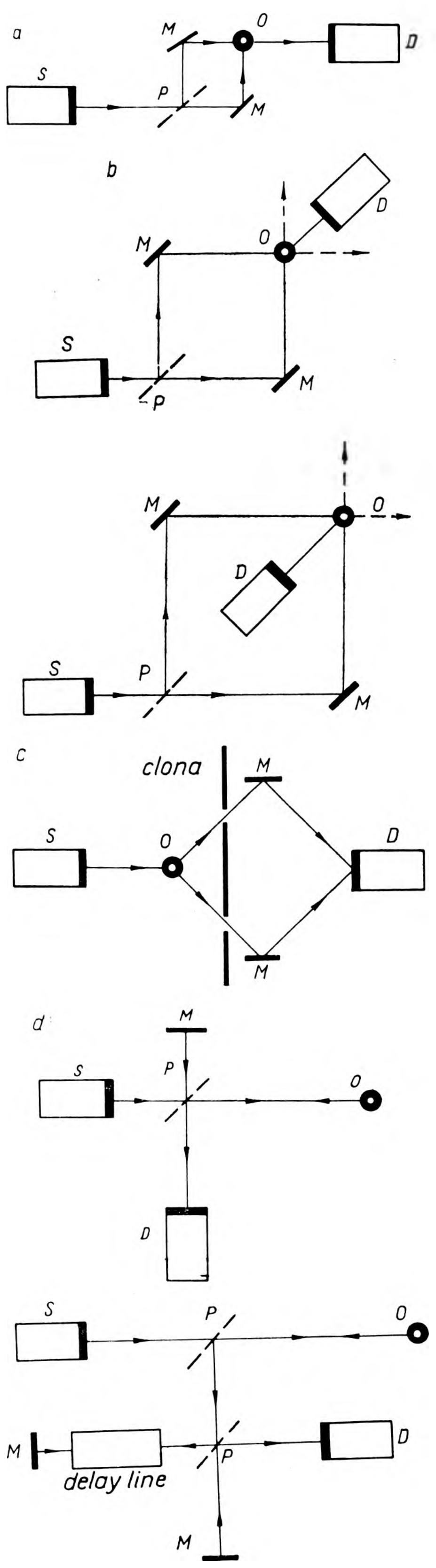

Fig. 4. a) Local oscillation (S — source, O — object, D — detector, M — mirror, P— semitransparent mirror,) b) different, c) symmetrical, d) Michelson interferometer

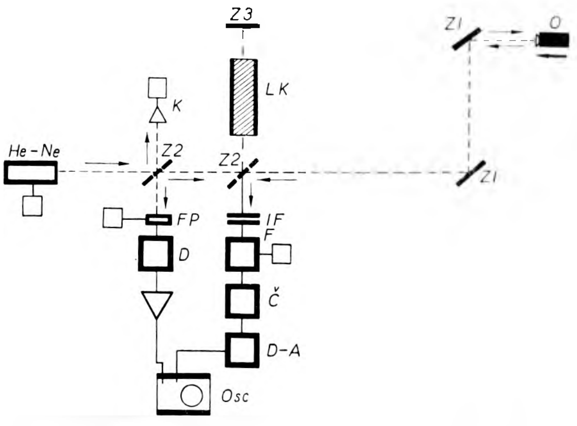

Fig. 5. LDV — experimental arrangement

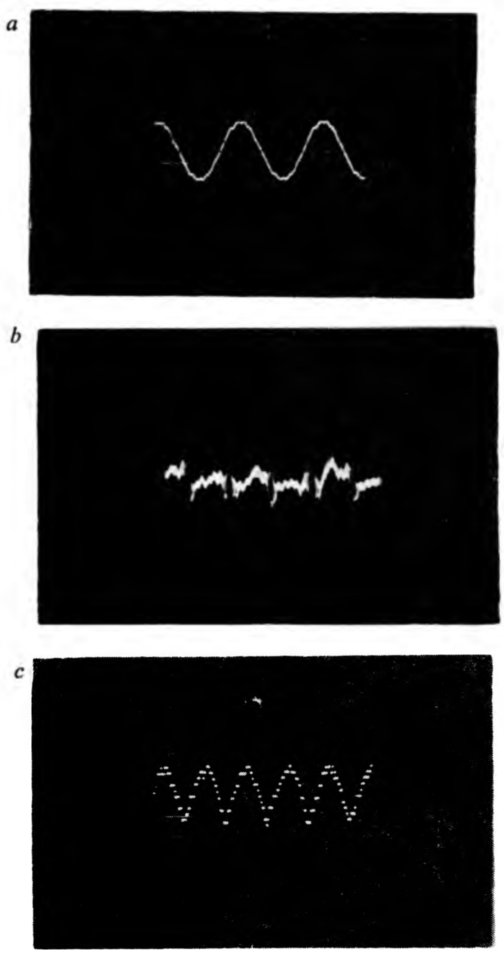

Fig. 6. a) Loudspeaker, b) photomultiplier, c) record

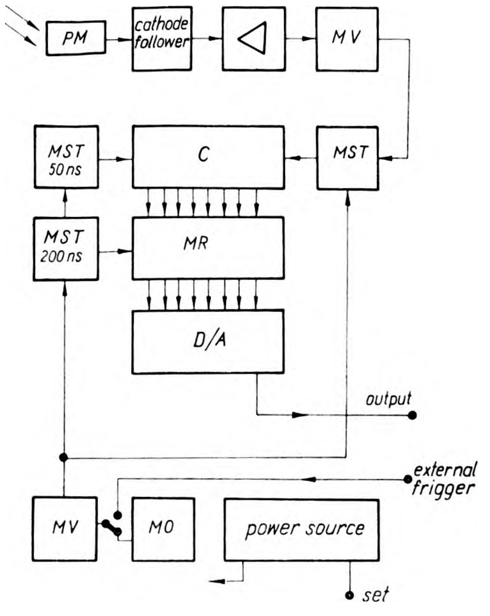

Fig. 7. Electronics circuit:
PM — photomultiplier, *MV* — multivibrator, *MST* — monostable circuit, *C* — counter, *MR* — memory, *D/A* — digital-analogue convertor, *MO* — master oscillator, *SC* — oscilloscope

VUVET 61 PK 502 was used as a detector*). The moving cbject was simulated by means of flat glass plate connected firmly to the diaphragm of a loudspeaker. The maximum obtainable speed was only few cm/s. The experimental arrangements is shown in fig. 5. The oscillogram of the current exciting the loudspeaker and the signal from the photomultiplier are shown in fig. 6a and 6b, respectively.

The Doppler frequency was measured directly by employing a counter. The measuring interval was chosen 33 μs. The digital information has been converted in to the analogous one and displayed on the oscilloscope (fig. 6c). Principal scheme of the electronic circuit is shown in fig. 7.

*) The detecting area was limited by a 1 mm diaphragm placed in front of the photomultiplier.

Acknowledgement

The author would like to express his gratitude to the chairman of the 3rd Czechoslovak-Polish Optical Conference Prof. RNDr. B. Havelka, Dr. Sc. for invitation to present this paper, to Ing. D. Vavrouch, CSc. for the information about the apparatus at the Institute of Scientific Instruments Czechoslovak Academy of Sciences in Brno, and to Ing. J. Veselý who performed some experiments at the Faculty of Nuclear Science and Physical Engineering.

Лазеры и их применение в оптоэлектронике

Обсуждена применимость лазеров в различных областях оптоэлектроники. Особое внимание уделено механизму и методу согласования.

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Received, November 26, 1976