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Matrix laser IR-visible image converter

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***Abstract*.** **A new type of a focal matrix IR-visible image converter is proposed. The pixel IR detectors of the matrix are tunable microcavities of VCSEL (vertical-cavity surface emitting laser) semiconductor microstructures. The image conversion is performed due to the displacements of highly reflecting cavity mirrors caused by thermoelastic stresses in their microsuspensions appearing upon absorption of IR radiation. Analysis of the possibilities of the converter shows that its sensitivity is $10^{-3} - 10^{-2}$ K and the time response is $10^{-4} - 10^{-3}$ s. These characteristics determine the practical application of the converter.**

Keywords: *matrix IR image converter, cavity mirror microsuspension, visible semiconductor laser.*

It is known [1] that the human eye cannot see in complete darkness an object whose temperature is below 700 K. At the same time, an IR-visible image converter allows one to observe an invisible object and analyse its state. Such a conversion provides a more complete use of the information potential of the IR range, which compares well in the information density with the visible range in broad daylight [2].

The directions in the development of IR image converters appearing in the last decade, in particular, increasing their sensitivity to 10^{-3} K can result in a qualitative passage from the observation of IR radiation sources to the possibility to see them in IR beams with a high information content.

By now many methods for thermal-visible image conversion have been proposed and realised. Nevertheless, investigations in this field become more and more extensive, which is explained at least by two circumstances, namely, by a considerable extension of practical applications of the IR region and by progress in the micromachine technology of thin films.

All the known converters can be divided conditionally into two groups. The first group includes converters in which IR radiation is converted to an electric current, for example, various thermal detectors [3]. The second group includes converters in which the up-conversion of the electromagnetic radiation occurs, i.e., IR radiation is converted to visible radiation without generating an electric current. An example of such a converter is a liquid-crystal converter [1].

Note that at present the most significant success is achieved in the development of the first-group converters, which attract the most interest. They include, first of all, uncooled microbolometer arrays (see review [4]), focal multiplexers, and pixel IR detectors, which are capacitive detectors [5]. This interest is caused by the high level of the development of the available manufacturing technology of microelectronic-mechanical elements. At the same time, the development of the second-group converters requires a more complex microelectronic-optomechanical technology, which is not widely available so far.

Therefore, the results obtained in this paper can stimulate a wider application of this complex technology, in particular, for the development and fabrication of various second-group converters.

Irrespective of its group, any IR image converter contains an optical system to form an image in the IR spectral region of interest, for example, on a focal matrix with pixels detecting IR radiation. As a rule, a pixel detector has a thin layer absorbing IR radiation and a sensitive element in thermal contact with this layer. As IR radiation is absorbed, the temperature of the sensitive element changes, resulting in a change in its parameters or properties. This allows one to perform the image conversion by using an appropriate interrogation scheme.

In this paper, we consider a second-group matrix converter, in which a multilayer vertical-cavity surface emitting laser (VCSEL) structure [6] emitting in the visible range is used as a pixel detector. The resonator of this laser can play the role of a sensitive element, as will be shown below. The output semi-transparent mirror of the resonator is a multilayer Bragg reflector with the reflection maximum at the wavelength λ_0. Radiation at this wavelength will form a visible monochromatic image of an invisible object. As a highly reflecting movable mirror, a metal film deposited on a bimaterial console or membrane suspension is used. The suspension is made to provide an air gap of width $\Delta \approx \lambda_0$ between the boundary of the active medium of the laser and this mirror [7].

We decided to use the VCSEL as a pixel of the matrix IR image converter for the following reasons. First, the VCSEL structure always emits at a single longitudinal mode because in this case the mode interval $\Delta\lambda_{\rm m} \approx \lambda_0^2/[2(nL + \Delta)]$ noticeably exceeds the width of the laser line equal to 10 – 20 nm

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(Fig. 1) (here, $L \approx 2\lambda_0$ is the length of the active medium of the laser and n is its refractive index, whose dispersion is neglected for simplicity). Under such conditions, a variation in the slit width will cause the shift of the laser line, providing thereby a controllable variation in the laser radiation intensity. Second, the manufacturing technology of this structure provides a high integration degree of pixel elements, which ensures a high spatial resolution of the image conversion process and permits the use of microprocessor technology to control the state of pixels of the focal multiplexer.

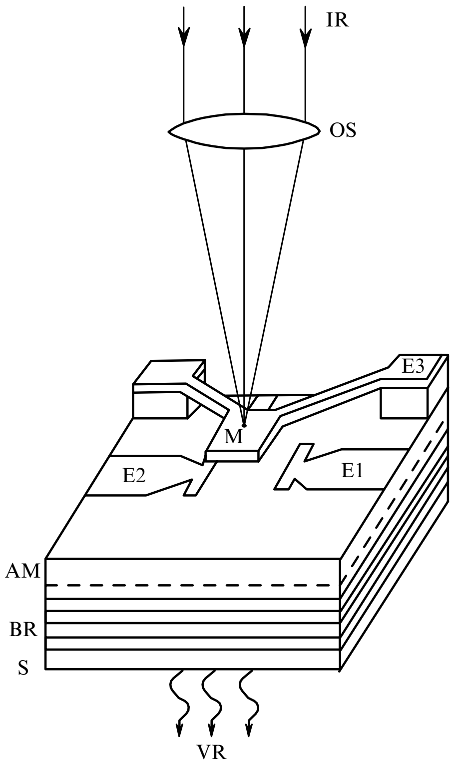

Figure 1. Scheme of the matrix pixel IR radiation converter: (S) pixel substrate; (BR) Bragg reflector; (AM) active laser medium; (M) movable resonator mirror with the console suspension; (E1, E2) injection current electrodes; (E1, E3) bias voltage V electrodes; (OS) optical system; (IR, VR) infrared and visible radiation.

We will assume that the highly reflecting mirror of the resonator is a metal film (for example, made of Au or Al), which is simultaneously one of the layers of a bimaterial suspension. The coefficient of thermal expansion α of the second layer of the suspension (consisting, for example, of SiN_x or SiO_2) should considerably differ from this coefficient for the metal film. In this case, it is possible to change the air gap width Δ under the action of the electrostatic force $F = \varepsilon_0 V^2 bl/\Delta^2$ (by applying the bias voltage V between the metal film and the active medium of the laser) or thermoelastic stresses appearing in the bimaterial suspension upon absorption of IR radiation in the film. To increase absorption, a special strongly absorbing layer is deposited on the external surface of the film. In the expression presented above, ε_0 is the permittivity of vacuum; and b and l are the geometrical parameters of the suspension, which in the case of a console are its width and length, respectively.

We consider the operation principle of our converter by the example of a single matrix pixel for a console suspension (Fig. 1).

Let the bias voltage be switched off initially ($V = 0$) and the optical IR channel be shut off, i.e., IR radiation is not incident on the suspension of the highly reflecting mirror and, therefore, thermoelastic stresses in this suspension are absent. Under these conditions, the injection pumping of the active medium provides the VCSEL emission at the wavelength λ_0 (Fig. 2).

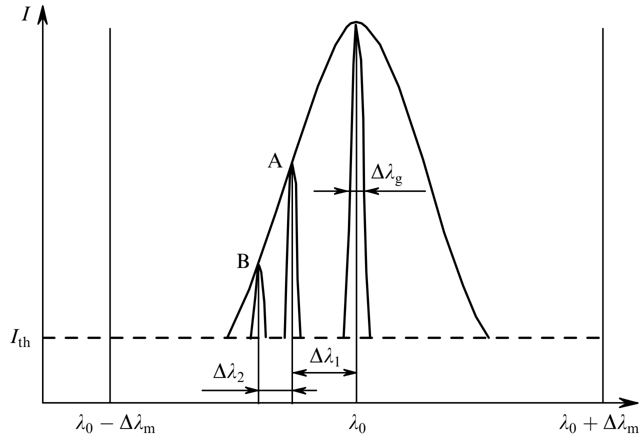

Figure 2. Lasing spectrum of a VCSEL pixel.

If we now switch on the bias voltage, the laser line will shift by the value $\Delta\lambda_1 \approx \lambda_0 W_1 (nL + \Delta)^{-1}$ (a new position of the laser wavelength is indicated by the point A in Fig. 2). The line shift is caused by the force F, which reduces the air-gap width Δ by the value $W_1 \approx Fl^3(1 - v^2)/(2t^3 bE)$ [8], where E, v, and t are the average (to simplify the problem) values of the Young modulus and the Poisson ratio, and the thickness of layers of the bimaterial suspension, respectively. As the voltage V is varied, the operating point A can be located both near the region where the lasing intensity is most sensitive to the gap width in the resonator and near the lasing threshold (at the fixed injection pump power), which is especially attractive in the case of membrane suspensions.

If we now open the optical channel, the IR radiation signal of power Φ formed by the optical system will be absorbed in the rear side of a movable mirror. This gives rise to thermoelastic stresses in the bimaterial suspension, resulting in the displacement of the highly reflecting mirror. The gap in the resonator decreases further by $W_2 = \Phi K(\alpha_1/\alpha_2, \chi_1/\chi_2, t_1/t_2, b, l)$, and the lasing mode shifts by $\Delta\lambda_2 \approx (\lambda_0 - \Delta\lambda_1) W_2 (nL + \Delta)^{-1}$ from the point A to the point B (Fig. 2). The laser power at the pixel, i.e., the VCSEL structure, lasing intensity will decrease, respectively. Thus, each of the pixels of the focal multiplexer will generate visible radiation, whose intensity is directly determined by the power Φ of the corresponding IR radiation. As a result, the visible image of the object will appear in the output plane of the focal multiplexer, which is observed in the IR range.

The function K in the expression for W_2 depends both on a combination of the geometrical parameters b, l and t of the suspension and the thermal characteristics α and χ of the layer material (χ is the heat conduction). This function determines in fact the photometric response of the micromechanical suspension of the highly reflecting mirror of the VCSEL resonator. In this case, the maximum of K is achieved by selecting appropriately the material of layers and the optimal relations between the corresponding parameters determining K. It follows from [9, 10] that $K = 4 \times 10^{-2}$ m W^{-1} for a console suspension.

Note that in the case of the bimaterial membrane suspension of the highly reflecting mirror, the converted image will be of the positive type because thermoelastic stresses in the membrane suspension will produce the displacement of the highly reflecting mirror in the direction opposite to that caused by the force F.

Due to the limited volume of the paper, we cannot describe here the converter in full details. However, we present some estimates characterising its potential possibilities for practical applications.

We will assume that the active medium ($n = 3.5$) of a multilayer VCSEL heterostructure is grown from a solid AlGaAs or AlGaAsP solution and the pulsed lasing wavelength is $\lambda_0 \approx 650$ nm. For definiteness, we assume that the geometrical parameters b and l of the console suspension of the highly reflecting mirror of the resonator are 8×10^4 and 4×10^4 nm, respectively, and they determine the size $S = bl$ of the area in which IR radiation is completely absorbed.

For the conventional IR region between 8 and 12 μm, we obtain $\Phi \approx 6.5 \times 10^{-2} S\sigma T^4 (d/f)^2$ W for radiation incident on the pixel area S, where σ is the Stephan–Boltzmann constant; d is the entrance pupil diameter; f is the focal distance of the optical system; T is the temperature of a remote extended IR radiation source. We assume for simplicity that $d/f = 1$ and $T = 300$ K. Then, $\Phi \approx 10^{-7}$ W for the IR range selected above, the corresponding displacement of the highly reflecting mirror is $W_2 = K\Phi \approx 4$ nm, and the shift of the laser mode is $\Delta\lambda_2 \approx \lambda_0 \times W_2/(nL + \Delta) \approx 0.5$ nm, which is noticeably greater than the laser linewidth $\Delta\lambda_g$, which, as can be expected, is $10^{-4} - 10^{-3}$ nm.

In principle we can assume that the shift $\Delta\lambda_2$ of the laser line is caused by the action of the background IR radiation with the characteristic temperature $T = 300$ K. In this case, by adjusting the bias voltage V (by decreasing it for the console suspension and increasing for the membrane suspension), we can return the operating point of the pixel detector to the initial position A if it is necessary to observe an object whose temperature differs from the background temperature by ΔT. In this case, as follows from the corresponding estimate, the variation range of the voltage V does not exceed 1–2 V.

The presence of an object with the temperature exceeding the background temperature by ΔT will cause an increase in the radiation power Φ incident on the pixel area S by the value

$$\Delta\Phi = \frac{S}{4}\left(\frac{d}{f}\right)^2 \left(\frac{\Delta M}{\Delta T}\right)_{\Phi} \Delta T,$$

where $(\Delta M/\Delta T)_{\Phi}$ is the so-called temperature contrast, which is 2.0 W m^{-2}K^{-1} for the chosen spectral range 8–12 μm (for the background temperature equal to 300 K) [3]. Then, $\Delta\Phi = 1.6 \times 10^{-9} \Delta T$ W K^{-1}.

The limiting detectable value of ΔT determining the sensitivity of the converter can be estimated by assuming that thermoelastic stresses in the suspension caused by a change in the radiation flux by $\Delta\Phi$ induce the spectral shift of the laser mode by its width, i.e., by $\Delta\lambda_g \approx 10^{-14}$–$10^{-13}$ m. Then, $\Delta T = 0.62 \times 10^9 (\Delta\lambda_g/\lambda_0)(nL + \Delta)/K$, and we obtain $\Delta T = 10^{-3} - 10^{-2}$ K for the selected parameters.

The real value of ΔT will probably noticeably exceed this estimate because, first, there exists the thermal noise of the suspension, and, second, it seems unlikely that the shift of the laser line only by its width can provide the required contrast of the visible image. The influence of the first circumstance can be substantially reduced by placing the matrix multiplexer in an evacuated volume. The influence of the second factor also can be diminished by forming the 'high-Q' spectral gain profile, in particular, by adjusting properly the pumping regime of the active medium of pixels.

The description of the matrix IR radiation converter presented above does not concern its response time, which is directly determined by the thermal time constant of a pixel. By assuming that heat transfer from the suspension and the active medium of the pixel occurs exclusively to the substrate, then, as follows from estimates, the characteristic time of the thermomechanical relaxation of the pixel will be a few fractions of millisecond, which is quite acceptable for this converter, for example, in the TV standard.

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