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Polarimetry of waveguiding heterostructures with quantum well-dots

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Abstract. The effect of the waveguide and the quantum well-dot active region on polarization of transmitted light in laser-like heterostructures was studied with the polarimetry technique. The waveguide structures with quantum well-dots were demonstrated to have almost no effect on the transmitted radiation polarization when it is parallel or perpendicular to active region layers. However, in the case of intermediate angle of linear polarization, the transmitted radiation represents a mixture of elliptically polarized and unpolarized light. The largest degree of depolarization found was at 45° of linear polarization angle of the input radiation. Depolarization was found to increase with decreasing of number of QWD layers and reaches 23% for a single layer.

Keywords: optical polarization, Stokes parameters, quantum well-dots, waveguiding heterostructures

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Поляриметрия волноводных гетероструктур с квантовыми яма-точками

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Аннотация. Методом поляриметрии исследовано влияние волновода и активной области лазерных гетероструктур на основе квантовых яма-точек на поляризацию проходящего излучения. Установлено, что волноводные структуры с квантовыми яма-точками практически не оказывают влияния на проходящее излучение с поляризацией, параллельной или перпендикулярной слоям активной области. Однако, при вводе излучения с промежуточным углом линейной поляризации, выходящее излучение представляет собой смесь эллиптически поляризованного и неполяризованного света. Обнаружено, что деполяризация излучения максимальна при угле поляризации входящего излучения 45°, при этом она обратно пропорционально зависит от количества слоев квантовых яма-точек в активной области, достигая 23% для однослойной структуры.

Ключевые слова: оптическая поляризация, параметры Стокса, квантовые яма-точки, волноводные гетероструктуры

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Introduction

At present time, there is a great interest in studies of quantum heterostructures with an intermediate properties between quantum wells and quantum dots [1], for example such as a quantum wires [2], well-island [3], wire-on-well [4], etc. Quantum well-dots (QWDs) are one of such type of structures, which can be described as InGaAs/GaAs quantum well (QW) modulated in thickness and composition or a superdense array of small InGaAs quantum dots (QDs). QWDs are free of some of the drawbacks of both QWs and QDs but keeps their key features. For example, QWDs have a significantly higher gain (absorption) compared to InAs/GaAs QDs, and moreover allow growing more than 15 stacked dislocation-free layers, which is hard to realize in case of InGaAs/GaAs QWs [5, 6]. QWDs have been intensively studied over the past decade. Recently, it was found that planar waveguides with QWDs demonstrate TE-selective ground state absorption [7]. The selectivity of absorption was found to strongly decrease with an increase in either the waveguide length or the number of QWDs layers. This behavior is highly likely due to a depolarization of radiation in the waveguide. In this work, the influence of a waveguide and the QWD active region on transmitted radiation polarization is studied by polarimetry technique. At the present time a lot of experimental studies of emission polarization of nanostructures have been published, but they dealt mainly with spontaneous or stimulated emission of the structures themselves [8, 9]. Transmitted light polarimetry has been investigated for passive optical waveguides [10]. To the best of our knowledge this is the first study of the of transmitted light polarimetry of waveguides with a nanostructure active region.

Materials and Methods

The samples based on AlGaAs *p-i-n*-structures, similar in design to typical edge-emitting lasers, were grown by metalorganic vapor-phase epitaxy (MOVPE) on a vicinal GaAs(100). The active region located in the center of the 800 nm thick GaAs waveguide layer contains 1, 2, 5, or 10 QWD layers separated with 40 nm thick GaAs spacers. Each QWD layer, in turn, is formed by deposition of 8 monolayers of $In_{0.4}Ga_{0.6}As$. Broad-area (50 μm and 100 μm wide) stripe waveguide samples of 2-mm length were studied in the experiment. Facet coatings were not used. The details of growth and processing can be found in other sources [1]. The scheme of the experimental setup is shown in Fig. 1.

A tunable laser (Sacher Lasertechnik) was set at wavelength 1050 nm corresponding to the QWD ground state absorption maximum [7]. A half-wave plate in combination with a Glan-Taylor prism was used as a rotator of linear polarization (LP). Then the radiation was focused on the front waveguide facet by the microlens. The sample was operated in the short circuit mode. The light focusing was monitored by a photocurrent level. The output radiation after passing through the combination of a quarter-wave plate and a linear analyzer was detected by a Si

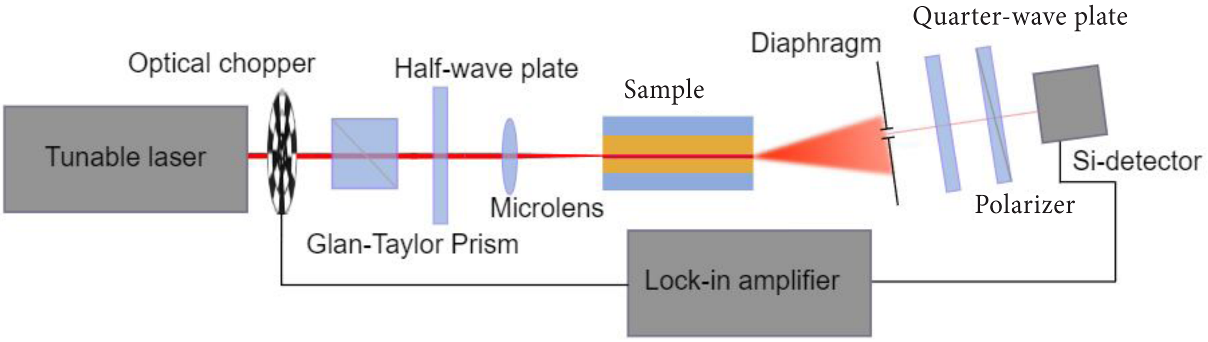

Fig. 1. Schematic representation of experimental setup

photodiode using a lock-in amplifier. To minimize a detection of radiation crosstalk, we used a diaphragm. Thus, we were able to define the Stokes parameters of radiation passed through the sample by caring out the six measurements of the flux *P* (table. 1) [11].

Table 1

Measuring of Stokes parameters

Measured flux	Experimental setup configuration
P_{H}	Linear polarizer is set to 0° (i.e., polarizer is set to TE-transmission). Quarter-wave plate is not used.
P_{v}	Linear polarizer is set to 90° (i.e., polarizer is set to TM-transmission). Quarter-wave plate is not used.
P_{45}	Linear polarizer is set to 45°. Quarter-wave plate is not used.
P_{135}	Linear polarizer is set to 135°. Quarter-wave plate is not used.
P_{r}	Linear polarizer is set to 45° and quarter-wave plate is set to 0° (by fast axe).
P_{L}	Linear polarizer is set to 135° and quarter-wave plate is set to 0°.

Results and Discussion

The obtained data were used to calculate the Stokes vector:

$$\boldsymbol{S}=\begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix}=\begin{bmatrix} P_H+P_V \\ P_H-P_V \\ P_{45}-P_{135} \\ P_R-P_L \end{bmatrix}. \tag{1}$$

These parameters allow us to separate the depolarized part of radiation and to plot polarization ellipses, which represent the trajectory of the electric field vector **E**. For instance, these ellipses are shown in Fig. 2 for single QWD layer sample and different initial LP. The unpolarized part of the radiation is schematically shown as a dash circle and input LP radiation is also marked as red dotted line.

Polarization parameters such as the degree of polarization (DOP), ellipticity, azimuth of ellipse orientation (major axis) have been calculated as described in insets of Fig. 3 and plotted as functions of the angle of the LP of input radiation, α (Fig. 3) for the given structures 2 mm in length with a different number of QWD layers (1, 2, 5, 10).

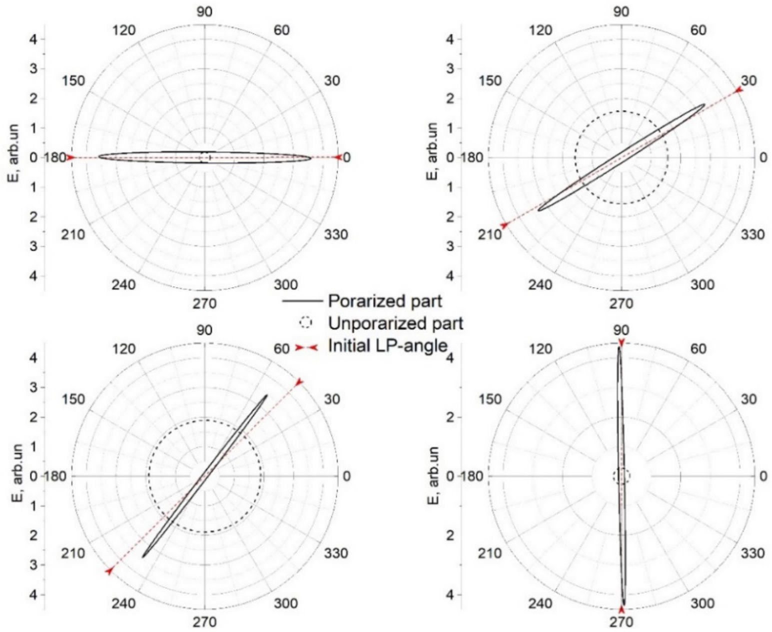

Fig. 2. Polarization ellipses of output radiation from single QWD layer sample. Unpolarized part of the radiation is schematically shown as a dash line circle. The angle of LP of input radiation is marked with red dotted line

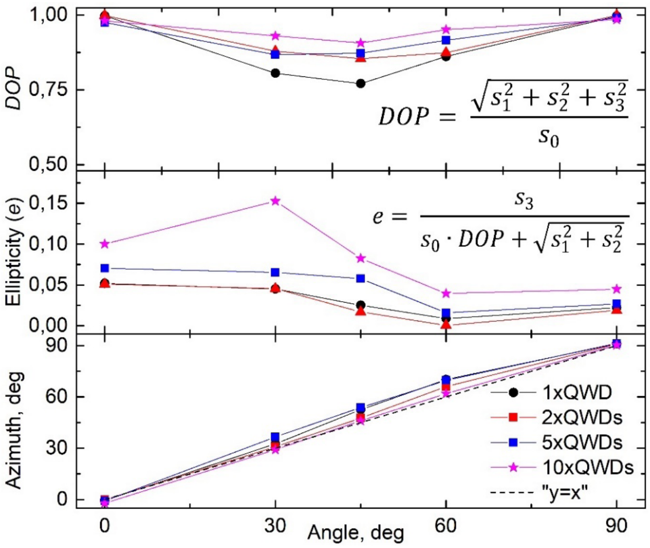

Fig. 3 Degree of polarization (DOP), ellipticity *e* and angle of ellipse orientation (azimuth) as functions of angle of LP of input radiation α for samples 2 mm in length with different number of QWD layers

In terms of polarization one can separate two different cases. In the first one, TE- or TM-polarization of the input radiation remains practically unchanged except of slightly increased ellipticity. Also, there are some differences in the amplitude of transmitted TE- and TM-polarized radiation arising from TE-selectivity of absorption of QWDs [7] which is out of the scope of the paper. In the second case, namely intermediate polarization angle α of the input radiation (not pure TE or TM) the transmitted radiation represents a mixture of depolarized and elliptically polarized light. The azimuth of the ellipse of the transmitted radiation follows, in general, the angle of LP of the input radiation α being slightly shifting towards the TM component. This shift occurs due to anisotropy of QWDs absorption (absorption of the TE component during transmission of the radiation in the waveguide) resulting in TM dominance at the end and, therefore, in a small rotation of the ellipse.

Dependences of ellipticity of the transmitted radiation on α are complicated. However, the tendency of increase of ellipticity with the number of QWD layers is clearly seen. We attribute this behavior to the presence of birefringence of the investigated samples due to both difference of effective index between TE and TM optical modes in the waveguide of the structures and birefringence of the QWDs themselves because of their dichroism. Therefore, for LP light with intermediate polarization angles, such waveguides represent a waveplate meaning that ellipticity of transmitted light may increase or decrease depending on the waveguide length and α. The experimental point for the 10xQWDs sample at $\alpha = 30°$ seems like an outlier which however does not affect the above tendency.

It is of the greatest interest to analyze the dependences of DOP. As discussed in [7], depolarization results in conversion of the TM-polarized light to TE-polarized one inside waveguides with QWDs. This effect causes strong absorption of TM-polarized radiation in long waveguide structures with QWDs, which is unexpected because QWDs active region predominantly absorb TE-polarized emission. It is the polarization conversion that is responsible for this phenomenon. As evident from Fig. 3, DOP is minimal at $\alpha \approx 45$ degrees and is as small as 0.77 (i.e., depolarization, (1-DOP) reaches 23%) in case of single QWD layer. Moreover, depolarization is tending to decrease with an increase in the number of QWD layers. This observation is contradicting to that reported earlier data [7], in which the larger QWD layer quantity resulted in the higher degree of the depolarization. We suggest that the increase in the number QWD layers leads to an increase in TE-absorption countervailing the effect of TM to TE conversion due to the depolarization. We are carrying out additional investigations to prove this suggestion.

Conclusion

Laser-like waveguide structures with different number of QWD layers were studied with polarimetry technique. Transmission of TE- or TM- polarized radiation through the waveguides was found to occur without significant change of polarization state, whereas transmission of linearly polarized light with intermediate polarization angle results in an output of elliptically polarized light with an addition of depolarized one. The depolarization reached 23% at 45° LP angle for single QWD layer structure, and is found to decrease with the number of QWD layers in the waveguide. The results obtained may be useful for engineering waveguide-based devices with a QWD-based active medium.

REFERENCES

1. **Maximov M.V., Nadtochiy A.M., Mintairov S.A., Kalyuzhnyy N.A., Kryzhanovskaya N.V., Moiseev E.I., Gordeev N.Y., Shernyakov Y.M., Payusov A.S., Zubov F.I., Nevedomskiy V.N., Rouvimov S.S., Zhukov A.E.,** Light emitting devices based on quantum well-dots, Appl. Sci. 10(3) (2020) 1038.
2. **Al Saqri N.A., Felix J.F., Aziz M, Kunets V.P., Jameel D., Taylor D., Henini M., Abd El-Sadek M.S., Furrow C., Ware M.E., Benamara M., Mortazavi M., Salamo G.,** Investigation of electrically active defects in InGaAs quantum wire intermediate-band solar cells using deep-level transient spectroscopy technique, Nanotechnology. 28(4) (2017) 045707.
3. **Yu Q., Li X., Jia Y., Lu W., Zheng M., Zhang X., Ning Y., Wu J.,** InGaAs-Based Well-Island Composite Quantum-Confined Structure with Superwide and Uniform Gain Distribution for Great Enhancement of Semiconductor Laser Performance, ACS Photonics 5 (2018) 4896–4902.
4. **Cho H., Toprasertpong K., Sodabanlu H., Watanabe K., Sugiyama M., Nakano Y.,** Stability and controllability of InGaAs/GaAsP wire-on-well (WoW) structure for multi-junction solar cells, J. Cryst. Growth 464 (2017) 86–93.
5. **Mintairov S.A., Kalyuzhnyy N.A., Maximov M.V., Nadtochiy A.M., Rouvimov S., Zhukov A.E.,** GaAs quantum well-dots solar cells with spectral response extended to 1100 nm, Electron. Lett. 51 (2015) 1602–1604.
6. **Nadtochiy A.M., Gordeev N.Y., Kharchenko A.A., Mintairov S.A., Kalyuzhnyy N.A., Shernyakov Y.M., Maximov M.V., Zhukov A.E., Berdnikov Y.,** Saturated layer gain in waveguides with InGaAs quantum well-dot heterostructures, J. Light. Technol. 39(23) (2021) 7479–7485.
7. **Kharchenko A.A., Nadtochiy A.M., Mintairov S.A., Shernyakov Y.M., Serin A.A., Gordeev N.Y., Maximov M.V., Zhukov A.E.,** Study of waveguide absorption in InGaAs ”quantum well-dots” heterostructures, Nano-Structures and Nano-Objects. 25 (2021) 100628.

8. **Yu Q.N., Jia Y., Lu W., Wang M.Q., Li F., Zhang J., Ning Y.Q., Wu J.,** Experimental characterization of true spontaneous emission rate of optically-pumped InGaAs/GaAs quantum-well laser structure, AIP Advances 7(8) (2017) 085319.

9. **Konishi K., Nomura M., Kumagai N., Iwamoto S., Arakawa Y., Kuwata-Gonokami M.,** Circularly polarized light emission from semiconductor planar chiral nanostructures, Physical review letters 106(5) (2011) 057402.

10. **Erofeeva M.S., Dmitriev A.L.,** High-accuracy IR polarimetry of waveguide optical elements, Journal of Optical Technology. 74(6) (2007) 419–423.

11. **Bass M., Van Stryland E.W., Williams D.R., Wolfe W.L., Bowers J.E., Wey Y.G.,** Handbook of Optics: Fundamentals, Techniques and Design. McGraw-Hill, (1995) 22.8–22.10.

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