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LASER METHOD OF MEASURING REFRACTIVE INDEX OF A TRANSPARENT SUBSTANCE IN THE TERAHERTZ RANGE

Measurement of the refractive index of transparent materials in the terahertz (THz) range required for the development of devices and systems that operate in this range. Submillimeter lasers are one of the most affordable sources of coherent THz radiation. They have features that allow you to measure the refractive index of transparent materials. The method for on-line measuring the refractive index of transparent materials in the terahertz range is represented. The measurable substance is placed in a quasi-optical resonator. Measurements are performed by means of coherent terahertz electromagnetic radiation. Performed test measurements of the refractive index. Justification reducing error of measurement of the refractive index, taking into account the physics of the processes in the space of resonance submillimeter laser system, we conducted. It was shown that the accuracy of measurement of the refractive index can be greatly increased by placing the test substance in the resonator THz laser. Presented techniques for measuring the refractive index of transparent materials in the THz range can be used in various fields of science, technology and medicine.

Keywords: *refractive index, coherent terahertz electromagnetic radiation, quasi-optical resonator, submillimeter laser.*

Formulation of the problem

Electromagnetic radiation of terahertz (THz) range (frequency range 0.1 ... 10 THz) currently is widely used in various fields of science, engineering, biology and medicine. Dielectric and metal-dielectric waveguides, and various quasi-optical systems - couplers, beam transmitters, valves, polarization rotators are used for the transmission and processing of terahertz radiation. Materials which are transparent to THz radiation, are used in these devices. Separating plates and lenses made of these materials. The value of the refractive index (RI), of the materials from which this devices are made, it is necessary to know in their manufacture. The optical thickness of the splitter plates must provide in-phase signal reflected from both of its surfaces. Therefore it is necessary to know the magnitude of the refractive index of the material separating the plates. A sufficiently accurate value of the refractive index of a particular material is not always available in the datasheets. In addition, composite and laminated materials (such as mica and PCB) have a large spread of the values of the refractive index. In these cases it is necessary to measure the magnitude of the refractive index. Many methods of measuring the refractive index, which are successfully used in the optical or in the radio frequency bands, are unacceptable in the THz range. Measurements in the THz range hampered, by the lack of high-power radiation sources and sensitive detectors. Furthermore, the diffraction divergence does not allow radiation beams to form narrow.

The aim of this work is to develop methods for measuring the refractive index of substances and materials in the THz range.

Main part

Laser methods of measuring refractive index of a transparent substance in the ТГц range we have developed. Lasers submillimeter (submm) range used for such measurements. It is possible to carry out operational measurements of the refractive index, which do not require high precision, as well as high-precision measurements.

Rapid measurement of the value of the refractive index enables the method using the measuring apparatus shown in fig. 1.

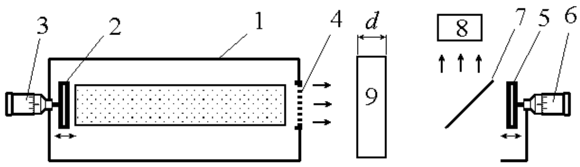

Fig. 1. The scheme of measuring device for rapid measurement of the refractive index of transparent materials in the THz range

The measuring device comprises a gas-discharge HCN- laser 1 with a wavelength λ = 337 μm. The laser resonator 1 is formed by a mirror 2 provided with a mechanism 3 for axial movement, and partially transparent mirror 4. Measuring resonator formed partially transparent mirror 4 and mirror 5, provided with axial displacement mechanism 6. Partially transparent plate 7 mounted at an angle of 45 ° between the mirrors 4 and 5. Partially transparent plate 7 stimulates the removal of part of the radiation energy in the receiver 8. Laser resonator 1 tuned to the resonant frequency, by moving the mirror 3. A whole number half-waves, located between the mirrors 2 and 4. Lasing occurs at THz laser resonator 1. Then, the measuring cavity is tuned by moving the mirror 5. Wherein, a whole number of half-wave arranged between the mirrors 4 and 5. Thus, energy builds up in the measurement resonator. Signal in the receiver 8 is increased several times. The magnitude of the signal increase at the receiver 8 depends on the quality factor of the resonator. Resonance processes in the measurement resonator does not have a significant impact on the auto-oscillatory process in the laser resonator 1. This is because the transmittance of the mirror 4 is small and is approximately 1-3%. Plate 9, which is to be measured, is established in the measuring resonator. This causes a change in the optical length of the measurement resonator. Consequently, there is an infringement of the resonance tuning of the measurement resonator. The mirror 5 to be moved along the axis, in order to make the adjustment at the resonance again. In this case, the distance between the mirrors 4 and 5 to be reduced. Поскольку величина ПП исследуемого вещества образца. This is because the refractive index of the plate 9 more than the refractive index of air. The movement ΔL of the mirror 5 is measured. Then the refractive index of the plate is calculated using the formula:

$$n_2 = \frac{d + \Delta L}{d} n_1, \qquad (1)$$

where d - the plate thickness of the test material; n_1 - the value of refractive index of air.

Absolute measurement error ΔL is about 5 ... 10 µm, it depends on the quality factor of the resonator and the error of measurement of mirror movement.

We have carried out test measurements of the refractive index of fluoroplastic using the measurement setup shown in Fig. 1. Fluoroplastic plate thickness d = 50, 200 and 300 micron, we measured. The value ΔL was 20, 80 and 120 µm, respectively. Calculation of the refractive index gives a value of 1.4 by the formula (1). A more accurate value of the refractive index can be obtained by increasing the thickness of the measured sample. This can be achieved by sequentially increasing the number of the measured plates. Thus it is necessary to make a gradual adjustment of the resonator. Package consisting of the ten fluoroplastic plates that have a thickness of d = 200 µm, we measured. The value ΔL was 880 µm. Calculation of the refractive index gives a value of 1.44 by the formula (1). This corresponds to reference data [1]. Consequently, this measurement setup allows the selection and sorting of plates made of materials that are transparent in the THz range. Measurement accuracy is increased by increasing the thickness of the test plates. However, the losses are increased in the measuring resonator. Q factor of the resonator is reduced as a result of this. This causes the expansion of the resonance peak power, and causes an increase in displacement measurement error ΔL, and adversely affects the accuracy of measurement of the refractive index. Additional mirror allows to slightly increase the quality factor of the resonator. This mirror is installed in the divider 7, in front of the receiver 8.

This measuring system can be used for measuring gaseous and liquid substances. The measuring cell is installed instead of a plate 9, for this. Reference substance and the test substance is placed alternately in the measuring cell. Air or vacuum is used as a reference substance, usually. Calculation of the refractive index of the substance is performed against a reference substance. This measuring cell may have a greater length d. This improves measurement accuracy by several orders of magnitude, if the test substance does not introduce a significant loss in the resonator.

A new method for measuring the refractive index is developed by us. This method can significantly reduce the measurement error. The material that is measured, is established between the mirrors of THz laser resonator, when measuring by this method [2]. These measurements can be made using the HCN-lasers, which have a useful feature - the single-frequency operation mode. HCN-laser emits radiation only if there are specific discrete distance between the resonator mirrors - when an integer number of half waves placed between the mirrors. Therefore, the laser resonator has a mechanism which performs the movement of the mirror along an axis. Moving the mirrors causes lasing individual bursts, with sharp peaks (fig. 2). The distance, which is equal to half the wavelength, there is between the sharp peaks.

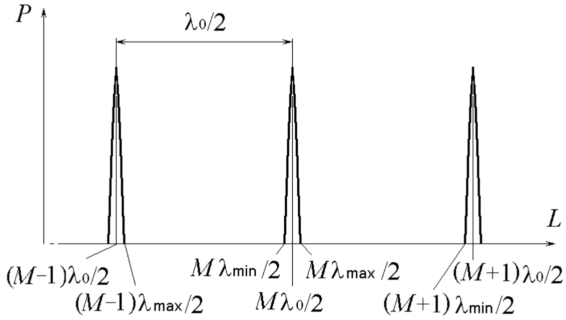

Fig. 2. The dependence of the laser power P of the resonator length L.

Lasing occurs only in the fundamental transverse mode. The wavelength changes when the mirror moves within the generation zone. Wavelength changes from the minimum (λ_{min}) to the maximum (λ_{max}) within the emission band of the active substance. The maximum lasing occurs at the central wavelength (λ_0). The frequency tuning range HCN-laser is about 10 ... 15 MHz. Mirror displacement interval within which lasing occurs is $M\Delta\lambda$ (where $\Delta\lambda$ - range of lasing wavelengths within the emission band of the active substance; M - the whole number of half waves to be placed between the mirrors). The magnitude of this interval ($M\Delta\lambda$) depends on the width of the emission band of the active substance, and also depends on the axial distance between the laser mirrors. This interval ($M\Delta\lambda$) is ~ 15 µm in HCN-laser having a resonator length of about 1 m. The distance between adjacent peaks of the laser power is 168.5 µm (half wavelength for this laser). If the refractive index of a substance changes in this laser (resonator length of about 1 m) by an amount $\Delta n/n \sim 10^{-6}$, it causes a change in the optical cavity length of 1 µm. This change in length can be measured with a mirror displacement mechanism, which is used in HCN-lasers. Thus, it is possible to measure the refractive index with high accuracy by using THz laser.

The test substance is placed inside the laser resonator for measuring the refractive index, by using this new method. Test substances may be solid or liquid, or gaseous. Transparent cell is required for the measurement, if the measured substance - liquid or gaseous. This measurement method is based on measuring the difference in distance between the laser resonator mirrors at two options for resonance tuning. The first option - it is when a transparent cuvette filled with reference material or vacuum. The second option - is when a transparent cuvette filled with the test substance. In both cases, the same number of half waves must be placed between the mirrors of the resonator, and this condition must be strictly observed. Laser system for measuring the refractive index of the gaseous substances is shown in fig. 3.

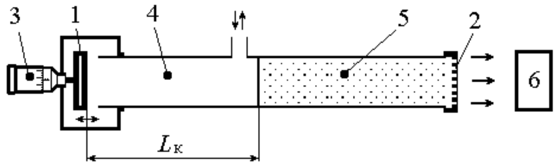

Fig. 3. Laser system for measuring the refractive index of the gaseous substances.

This measuring device comprises a THz laser (eg HCN laser). The laser resonator formed by mirrors 1, 2. Mirror 1 is equipped with a mechanism 3. This mechanism is used to move the mirror 1 along the axis of the resonator. Mirror 2 is partially transparent. Зеркало 2 является частично прозрачным. This mirror is used for the output of the laser radiation from the resonator. The laser beam enters the radiation detector 6. The measuring cell 4 and the container 5 with the laser active medium are located between the mirrors 1 and 2.

The sequence of measurements of gaseous substances is presented. First, create a vacuum in the measuring cell 4. Then, the laser resonator must be set to the center frequency of the emission line of the active substance. This adjustment is performed by moving the mirror 1 by a mechanism 3. Then, a gaseous substance that is necessary to investigate, is placed in the cell 4. This causes a change in the refractive index in the resonator. This causes a disturbance of the ideal resonator configuration, and a decrease in the lasing. Now move the mirror 1 is required by the mechanism 3, in order to again receive the maximum power lasing. This movement should be carried out simultaneously with the filling of the cuvette 4. Because it is very important, you need to adjust the resonator each time for the same peak power - $M\lambda_0/2$ (see fig. 2.). The amount of movement ΔL is determined on the micrometric scale mechanism 3. The refractive index of the test substance is determined by the formula 2:

$$n_2 = \frac{L_{\kappa 1}}{L_{\kappa 1} - \Delta L} n_1 \cong \frac{L_{\kappa 1}}{L_{\kappa 1} - \Delta L}, \quad (2)$$

where: $L_{\kappa 1}$ - the length of the measuring cell 4, up to when it filled with the test substance; ΔL - changing the distance between the mirrors 1 and 2 of the laser resonator.

The estimated error of measurement of the refractive index of ~ 10^{-6}, by using a cell 4 length of 1 m and a micrometric displacement device 3 with a scale division of 1 µm. The measurement error can be reduced by ~ 1-2 orders of magnitude, by increasing the length of the cell 4 and the use of more precise tracking mechanism 3. The ratio of the lengths of the cell 4 and the active medium 5 should be selected taking into account the attenuation of the laser radiation in the cell 4.

The scheme of the measurement setup shown in fig. 3, can also be applied to measure the refractive index of liquids. In this case it is advisable to place the laser axis in a vertical position. In this case, the boundary of a liquid and air (reference material) will smoothly move along the cell 4 when the cell 4 is gradually filled. This makes it possible to simultaneously adjust the axial length of the resonator.

The scheme of the measurement setup as shown in fig. 3 may also be used to measure the refractive index of solids. In these measurements the cell 4 is replaced by an air gap. Test material (a plate) is installed in the air gap. The measurement method is the same as described above. The value of the refractive index is calculated by the formula (1).

Conclusions

We have developed new methods that provide opportunities measuring the refractive index in the range of THz. These methods can be used in scientific research and engineering development.

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