EAST EUROPEAN JOURNAL OF PHYSICS. 4. 386-392 (2024)
DOI:10.26565/2312-4334-2024-4-45 ISSN 2312-4334

INTERFEROMETRIC LOCATING THE WAIST OF A LASER BEAM

Vyacheslav A. Maslov*, Konstantin I. Muntean
V.N. Karazin Kharkiv National University,4 Svoboda Sq., Kharkiv 61022, Ukraine
**Corresponding Author e-mail*: *v.a.maslov@karazin.ua*
Received September 18, 2024; revised November 11, 2024; accepted November 22, 2024

An interferometric method for determining the location of a laser beam waist has been developed, which implements the dependence of the wavefront curvature on its distance to the waist. The initial laser beam, the waist location of which must be determined, is split by a shear interferometer into reference and information beams, which form a spatially non-localized interference field in reflected light. The period of the interference fringes observed in any cross-section of the interference field carries information about the location of the waist of the initial laser beam relative to this section. The distance from the waist to the plane of recording the period of the interference fringes is calculated using the formulas of Gaussian optics. The fundamental difference of this method from currently known ones allows for increasing the accuracy of the obtained result while simultaneously reducing the laboriousness of the measurement process.
Keywords: *Laser; Gaussian beam; Waist location; Wavefront curvature; Shear interferometer; Two-beam interference; Period of the interference fringes*
PACS: 42.55.Lt; 42.60.Da; 42.25.Bs; 47.32.C–

INTRODUCTION

Determination of the spatial parameters of a laser beam is of fundamental importance in such practical applications as laser material processing [1], including laser welding [2] and cutting [3] in the aerospace and automotive industries, laser powder metallurgy [4], laser therapy in medicine [5], optical metrology [6], development of refractive [7], diffractive [8] and reflective [9] optics, spatial light modulators [10], acousto-optic deflectors [11], optical phased arrays [12] and other optical components [13], matching of eigenmodes of optical devices [14], efficient input of laser radiation into fiber systems [15], precision laser tracing [16], and others.

Currently, the Gaussian model of a laser beam is widely used to describe the process of radiation propagation, both in various optical systems and in free space. Although this model does not satisfy Maxwell's equations, it provides acceptable accuracy of engineering calculations for most typical optical systems and satisfactory agreement with experimental results. The simplest Gaussian model describes the spatial characteristics of a stigmatic laser beam with cylindrical symmetry. The location of the laser beam waist plays a fundamental role in the Gaussian model, since it establishes the origin of the coordinate system, which must be determined with the highest possible accuracy. From a fundamental point of view, the algorithm for determining the waist location is completely clear. First, taking into account the length of the laser resonator and the radii of curvature of its mirrors, it is necessary to calculate the spatial parameters of the radiation beam, including the location of the waist inside the resonator, following the classic article by Kogelnik and Lee [17]. Then we sequentially calculate the change in the location of the beam waist after passing through each element of the optical system, using the thin lens formula and taking into account the thickness and refractive index of both focusing and non-focusing optical elements. This theoretically clear approach is practically of little use, since it involves extensive calculations and, for a number of reasons, does not provide high accuracy of the calculation results. Therefore, laser specialists prefer to find the location of the waist experimentally.

To this time, a number of experimental methods have been developed for determining the location of the waist [18-36] for laser radiation sources with different spatial, temporal, power and spectral characteristics. The very existence of a large number of methods confirms that all of them are unsatisfactory due to either insufficient versatility or due to the relatively low accuracy of the measurement result.

The currently valid international standard ISO 11146-1/2/3:2021 [37 – 39] recommends determining the location of the waist by measuring the beam widths in at least 10 different sections located along the optical axis on both sides of the waist, with the measurement of the radiation density distribution in each section repeated at least five times. The obtained results are approximated by a hyperbolic dependence, and the vertex of the hyperbola indicates the location of the waist. However, such a method can rarely be implemented, as in practice the waist is usually inaccessible for direct measurements or does not physically exist. In this case, the standard recommends forming an artificial waist with an aberration-free focusing element, carrying out the above measurement procedure and calculating the location of the artificial waist. Then, based on the parameters of the focusing element and the distances from its main planes to the artificial and original waists, it is necessary to calculate the location of the original waist according to [17]. The ISO 11146 standard requires the use of a CCD camera to measure beam widths, which are determined by calculating the first and second moments of the radiation power density distribution using the formulas given in the standard. If a CCD camera is

Cite as: V.A. Maslov, K.I. Muntean, East Eur. J. Phys. 4, 386 (2024), https://doi.org/10.26565/2312-4334-2024-4-45

unavailable or cannot be used for any reason, the standard provides for the following alternative methods for measuring beam widths: the variable aperture method, the Foucault knife-edge method, the moving slit method, which are used when the radiation beam width is large, its power is high, or when CCD cameras with a suitable spectral range are not available.

Thus, all known methods for determining the location of the waist, except diffraction methods [23, 24] and specific ionization methods [21, 32], which require direct access to the waist, implement the relationship between the width of the laser beam in any section and the distance from this section to the beam waist. The main disadvantages of the known methods are as follows:

– reduced accuracy of measurement of radiation beams with low divergence, which are of greatest practical interest. As is known, such beams have a large width, which changes little from section to section. In this case, even a small error in measuring the beam width, as shown in [40], leads to a large error in the measurement result. In addition, wide-aperture focusing elements have increased aberrations, which further worsens the accuracy of the result;

– a certain labor intensity, since in order to increase the accuracy of the measurement result, it is necessary to repeatedly measure the beam width in the maximum possible number of its sections at the maximum possible distance between the sections.

The purpose of this work is to increase the accuracy of determining the waist location of a laser beam while simultaneously reducing the laboriousness of the measurement process.

THEORETICAL RELATIONS

Based on the relationship between the curvature $R(z)$ of the wavefront at any point of the optical axis of the laser beam and the distance from this point to the beam waist, an interferometric method is proposed for determining the location of the laser beam waist [41], which does not require direct access to the waist. According to this method, the original laser beam, the location of the waist of which must be determined, is split into information and reference coherent beams that form a non-localized two-beam interference pattern in the space. This pattern is similar to the spatial interference pattern from two coherent point sources, i. e. it is a family of nested two-sheet hyperboloids of revolution with foci at the location of the imaginary waists of the laser beams. As is known, the intensity of the two-beam interference field at any point in space depends only on the wavelength of the radiation, the distance between the two sources, and the distance from the observation point to the origin. Knowing the wavelength of the radiation, the distance between two, imaginary in our case, waists and the period of the interference pattern in any registration plane, we can calculate the distance from the period registration point to the origin of coordinates, and therefore determine the location of the waists. Thus, the problem of determining the location of the original waist, which is inaccessible or does not physically exist, is reduced to determining the parameters of the interference pattern from the pair of imaginary waists we have created.

Analysis of the known methods of forming two interfering beams from one original beam shows that in our case, only a system of two parallel planes is applicable, which forms two imaginary waists, the distance between which is determined only by the parameters of the formation system itself. Any other known system (Fresnel biprism, Biye bilens, Fresnel and Lloyd mirrors, etc.) forms sources, the distance between which also depends on the unknown distance between the plane of the waist of the original laser beam and the formation system. The technical implementation of the system of two parallel planes can be a transparent plane-parallel plate or a Michelson interferometer tuned to zero order. In the case of using a plane-parallel plate, the distance 2C between the imaginary waists of the interfering beams is equal to (Figure 1):

$$2C = \frac{2d\cos\alpha}{(n^2 - \sin^2\alpha)^{\frac{1}{2}}}, \tag{1}$$

where d is the plate thickness; n is the refractive index of the plate material; α is the angle of incidence of the laser beam on the plate.

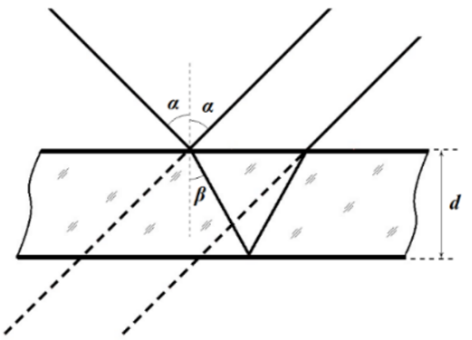


Figure 1. Ray path in a plane-parallel plate.

It follows from formula (1) that the distance between the imaginary waists of the interfering radiation beams, i.e. the position of the foci of the family of two-sheeted hyperboloids, depends on the angle of incidence of the laser beam on the plane-parallel plate, and, therefore, the interference pattern of two Gaussian beams formed by a system of two parallel planes is not a complete analogue of the classical interference pattern from two real point sources. It follows from Figure 2 that a complete analogy of interference patterns should be observed only in the far field of the laser beam.

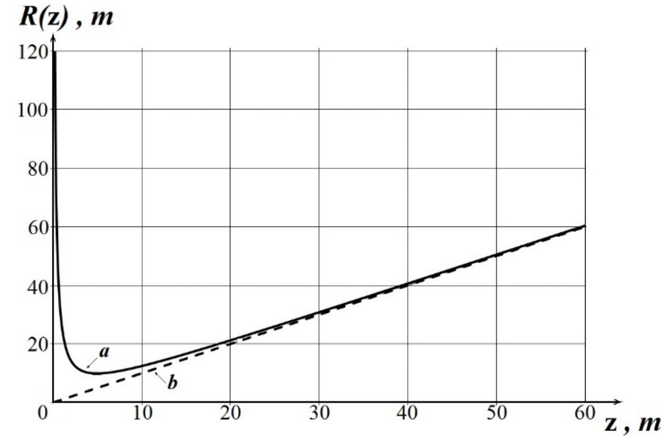


Figure 2. Dependence of the wave front curvature on the distance to the radiation center
a) Gaussian beam (λ = 0.6328 μm, ω_0 = 1.0 mm), b) point source.

When observing the interference pattern in an arbitrary recording plane, the interference fringes can be calculated as the lines of intersection of this plane with the family of hyperboloids. The shape, width and direction of the fringes depend only on the selected orientation of the recording plane.

Let us consider the cases of observing an interference pattern that occur in practice. The origin of coordinates is placed in the middle between the imaginary waists, the abscissa axis is drawn through the centers of both waists (Figure 3). In all cases, the observation plane is at a distance of $l >> 2C$ from the origin of coordinates. The following cases of the location of the photorecorder's light-sensitive area are fundamentally possible:

1) the ordinate axis passes through the center of the photorecorder's light-sensitive area normally to it. An interference pattern is observed in the form of a series of practically equidistant fringes, which can be considered straight with high accuracy;

2) the photorecorder's area is located at an angle to both coordinate axes - this is the case most often realized in practice when measuring the spatial parameters of a laser beam. The interference pattern is a family of curved nonequidistant fringes;

3) the abscissa axis passes through the center of the photorecorder's light-sensitive area normally to it. The interference pattern has the form of a family of concentric rings.

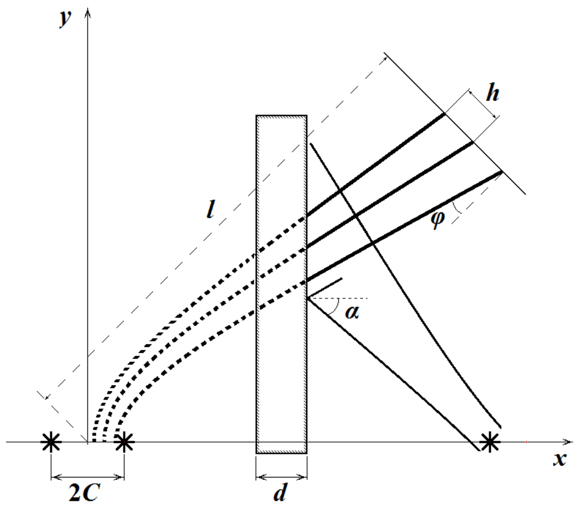


Figure 3. Scheme of formation of interfering beams

These three cases exhaust the entire set of observed interference patterns. When forming an interference pattern using a plane-parallel plate, all three positions of the recording plane can be obtained by changing the angle of incidence of the radiation beam on the plate. When forming an interference pattern using a Michelson interferometer adjusted to the zero order, the third case of observation is realized.

The period h of the interference fringes depends on the distance l between the recording plane and the origin. Solving together the equation for the optical path difference between the interfering beams and the equation for the recording plane, we obtain, taking into account (1), a calculation formula for determining the distance from the recording plane to the origin of coordinates by the period of the interference fringes

$$l = \frac{(h\, d \sin 2\alpha \cos^2 \alpha\, [\cos(\alpha+\varphi) + \mathrm{tg}\alpha \sin(\alpha+\varphi)]^2}{\lambda (n^2 - \sin^2 \alpha)^{\frac{1}{2}}},$$

where λ is the radiation wavelength; φ is the angle of incidence of the radiation beam on the recording plane. If the recording plane is placed perpendicular to the interfering beams, which is almost always possible, then $\varphi = 0$ and the calculation formula is simplified

$$l = \frac{h\, d \sin 2\alpha}{(n^2 - \sin^2 \alpha)^{\frac{1}{2}}}. \tag{3}$$

When using a Michelson interferometer, it is more convenient to measure the diameters of concentric rings instead of the fringe period. In this case, the calculation formula takes the following form

$$l = \left[\frac{d\,(D_{n+1}^2 - D_n^2}{\lambda n}\right]^{\frac{1}{2}},$$

where d is the thickness of the equivalent air plate of the Michelson interferometer; D_n and D_{n+1} are the diameters of any two adjacent interference rings.

Thus, by setting the angle of incidence of the laser beam on a plane-parallel plate and measuring the period of the interference fringes in the recording plane, we determine the distance from the recording plane to the origin using the above formula.

We will estimate the measurement error of the waist location by differentiating formula (3):

$$\frac{\delta l}{l} \approx \left[\left(\frac{\delta h}{h}\right)^2 + \left(\frac{\delta d}{d}\right)^2 + \delta\alpha^2 + \left(\frac{\delta\lambda}{\lambda}\right)^2 + \delta n^2\right]^{\frac{1}{2}}.$$

Typical values of the error components are as follows: $\delta h/h \approx 10^{-3}$; $\delta d/d \approx 10^{-4}$; $\delta\alpha \approx 10^{-4}$, $\delta\lambda/\lambda \approx 10^{-6}$; $\delta n \approx 10^{-4}$, which allows us to estimate $\delta l/l \approx 10^{-3}$.

It is worth noting the feature of the above-described interference measurement method, which distinguishes it from the known methods of measuring the spatial parameters of a laser beam and allows us to consider it promising for measuring the location of the waist of beams with small (on the order of fractions of an angular second) divergence angles. For example, in known methods, a small difference in beam widths, which is measured with a large error even for large beam divergence angles, tends to zero as the divergence angle decreases, which leads to a complete loss of the information contained in it. In the described interferometric method, the value of the informative parameter – the period of the interference pattern – increases with decreasing beam divergence angle, which allows us to advance in measuring the waist location for beams with small divergence angles beyond known methods by changing the parameters or design of the interference pattern formation system.

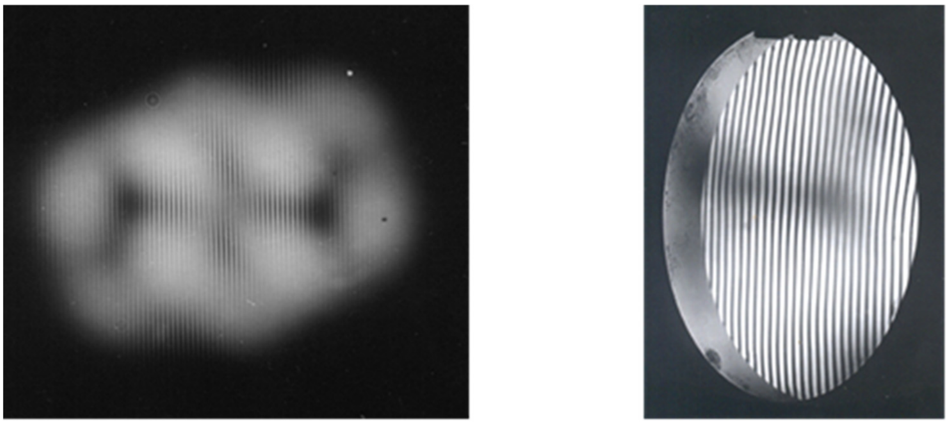
VALIDATION OF THE INTERFEROMETRIC METHOD

The following equipment was used to confirm the operability and accuracy of the interferometric method: He-Ne laser LG-56 with a plane-sphere resonator and a radiation wavelength of 0.632816 μm, a plane-parallel plate from the OSK-2 optical bench kit, 20.75 mm thick, made of K8 optical glass with a relative refractive index of $n = 1.514627$ for a laser wavelength, a collimator from the OSK-2 bench with a focal length of 1600 mm, a goniometer GS-5, two 1st-category geodetic rods with a nominal length of 1 meter, an indicator bore gauge NI-50 18–50, a microdensitometer MF-2; screens, adjustment tables, sheet film.

The tests were carried out as follows. The waist of the original laser beam of the LG-56 coincides with the surface of its output flat mirror. The location of the waist of the original laser beam was measured by the section method and the above-described interferometric method. Then the divergence of the beam was reduced using a collimator and the changed location of the beam waist was again measured by both methods. Consistent application of this procedure allowed us to obtain and measure a series of beam waist position values in the divergence angle range from ~ 10' to ~ 3".

The laser beam width was measured using the section method using screens with sheet photographic film, successively installed at different distances from the waist with a step of 5 m. The maximum distance from the output flat mirror of the laser was 75 m. The distance from the output mirror of the laser was set by successively moving two geodetic rods with a nominal length of 1 m. A screen with photographic film was placed at the measured distance. After processing the film, the diameter of the radiation spot obtained on it at the half-intensity level was measured using an MF-2 microdensitometer. The waist position was determined according to ISO 11146-1 by approximating the measurement results with a hyperbolic function.

The waist position was measured using the interference method using a standard plane-parallel plate from the OSK-2 optical bench with a thickness of 20.75 mm. The plate was mounted on the goniometer's rotary table so that the front reflecting surface of the plate coincided with the axis of rotation of the table. The angle of incidence of the laser beam on the plate varied within the range 0° ÷ 45°. The initial distance from the laser output mirror to the front surface of the plane-parallel plate was 75 m and was set, as in the previous case, by the method of repositioning the geodetic rods. A screen with a sheet of photographic film was placed at a distance of 1 m in the radiation beam reflected from the plate to record the interference pattern. A typical appearance of the obtained interference patterns is shown in Figure 4. Processing and photometry of the films were carried out in the same way as in the previous case. The location of the waist relative to the plane of recording the interference pattern was determined by calculation using the above formula (3).



a b

Figure 4. Interference patterns for beams with different divergence θ
a) θ = 8'15"; b) θ = 1'48" (reduced by 3 times)

DISCUSSION OF RESULTS

As a result of testing the measuring devices described above, the following was established:

— for the initial beam of radiation from the LG-56 laser with a divergence angle of ~ 10', both methods give results that coincide with each other with an accuracy of about 2 %;

— as the divergence angle decreases, i. e. when the location of the waist changes, the accuracy of the coincidence of the results decreases;

— the section method recommended by ISO 11146-1 is advisable to use to determine the location of the beam waist with a divergence angle exceeding 30", while the measurement error is about 10 %. The reason for limiting the measurement range is an increase in the measurement error in determining the location of the waist;

— the interference method is advisable to use to determine the location of beam waists with divergence angles exceeding 5', while the measurement error is no more than 5 %. The reason for limiting the measurement range is a decrease in the number of interference fringes observed in the radiation beam reflected from the plate to two. It is assumed that the measurement range can be expanded by changing the dimensions of the plane-parallel plate.

CONCLUSIONS

An interferometric method for determining the location of a laser beam waist has been developed, implementing the known relationship between the curvature of the wavefront in any cross-section of the radiation beam and the distance from this section to the beam waist. The tests conducted confirmed the operability of the interferometric method for determining the location of the laser beam waist, and the results obtained allow us to recommend this method as the most accurate of those currently known.

The laboratory testing process was carried out using fairly complex and bulky universal optical devices and precision measuring instruments. The development of a specialized device controlled by a microcontroller will significantly reduce the time of a single measurement by simplifying the operations of optical adjustments, setting the measurement angle, the process of scanning the interference pattern and processing the obtained data.

It should also be noted that, due to the significantly greater complexity of operation, the Michelson interferometer is advisable to use for unique measurements in cases where the use of wide-aperture plane-parallel plates of large thickness and weight is limited by the technological capabilities of their manufacture. The use of the Michelson interferometer is designed for future needs, while the existing level of needs can be fully satisfied by using those plane-parallel plates, the industrial production of which has been mastered at present.

ORCID
Vyacheslav A. Maslov, https://orcid.org/0000-0001-7743-7006; **Konstantin I. Muntean,** https://orcid.org/0000-0001-6479-3511

REFERENCES

[1] Mohl, S. Kaldun, C. Kunz, F. A. Muller, U. Fuchs, and S. Graf, "Tailored focal beam shaping and its application in laser material processing", J. Laser Appl. **31**, 042019 (2019). https://doi.org/10.2351/1.5123051
[2] Y. Mi, S. Mahade, F. Sikstrom, I. Choquet, S. Joshi, and A. Ancona, "Conduction mode laser welding with beam shaping using a deformable mirror", Opt. Laser Technol. **148**, 107718 (2022). https://doi.org/10.1016/j.optlastec.2021.107718
[3] N. Levichev, P. Herwig, A. Wetzig, and J.R. Duflou, "Towards robust dynamic beam shaping for laser cutting applications", Proc. CIRP, **111**, 746 (2022). https://doi.org/10.1016/j.procir.2022.08.116
[4] A.R. Bakhtari, H.K. Sezer, O.E. Canyurt, O. Eren, M. Shah, and S. Marimuthu, "A review on laser beam shaping application in laser-powder bed fusion", Adv. Eng. Mater. **26**, 2302013 (2024). https://doi.org/10.1002/adem.202302013
[5] O. Savchenko, in: *Laser technologies in orthodontic practice – Achievements and prospects, Conference proceedings of the International scientific and practical conference* (Seoul, Republic of Korea, 2019), pp. 109-114, https://doi.org/10.36074/22.12.2019.v1.35
[6] K.J. Gasvik, *Optical Metrology*, 3rd ed., (John Wiley & Sons, Ltd, 2002).
[7] H. Le, P. Penchev, A. Henrottin, D. Bruneel, V. Nasrollahi, J.A. Ramos-de-Campos, and S. Dimov, "Effects of top-hat laser beam processing and scanning strategies in laser micro-structuring", Micromachines, **11**, 221 (2020). https://doi.org/10.3390/mi11020221
[8] A. Forbes, F. Dickey, M. DeGama, and A. du Plessis, "Wavelength tunable laser beam shaping", Opt. Lett. **37**, 49 (2012). https://doi.org/10.1364/OL.37.000049
[9] M.A. Moiseev, E.V. Byzov, S.V. Kravchenko, and L. L. Doskolovich, "Design of LED refractive optics with predetermined balance of ray deflection angles between inner and outer surfaces", Optics Express, **23**, A1140 (2015), https://doi.org/10.1364/OE.23.0A1140
[10] C. Rosales-Guzmán, and A Forbes, "How to shape light with spatial light modulators," SPIE, **30**, 57 (2017).
[11] T. Häfner1, J. Strauß, C. Roider, J. Heberle, and M. Schmidt, "Tailored laser beam shaping for efficient and accurate microstructuring", Applied Physics A, **124**, 111 (2018). https://doi.org/10.1007/s00339-017-1530-0
[12] C. Halbhuber, "Heat conduction joining with the multispot focusing lens: Joining plastics and metal", PhotonicsViews, **19**, 60 (2022). https://doi.org/10.1002/phvs.202200044
[13] A.G. Nalimov, V.V. Kotlyar, S.S. Stafeev, and E.S. Kozlova, "Metalens for detection of a topological charge", Optical Memory and Neural Networks, **32**, S187 (2023). https://doi.org/10.3103/S1060992X23050144
[14] I.V. Petrusenko, and Yu.K. Sirenko, "Generalized mode-matching technique in the theory of guided wave diffraction. Part 3: wave scattering by resonant discontinuities", Telecommunications and Radio Engineering, **72**, 555 (2013). https://doi.org/10.1615/TelecomRadEng.v72.i7.10
[15] A.E. Mandel, and A.S. Perin, *Study of the efficiency of radiation input and losses at the joints of optical fiber*, (TUSUR, Tomsk, 2018). https://studfile.net/preview/16874330 (in Russian)
[16] O.B. Kovalev, I.O. Kovaleva, and V.V. Belyaev, "Ray tracing method for simulation of laser beam interaction with random packings of powders", AIP Conf. Proc., **1939**, 020028 (2018).https://doi.org/10.1063/1.5027340
[17] H. Kogelnik, and T. Li, "Laser beams and resonators", Appl. Opt. **5**, 1550 (1966). https://doi.org/10.1364/AO.5.001550
[18] J.A. Arnaud, "Gaussian laser beam-waist radius measuring apparatus", Patent United States No. 13,612,885 (10 Dec. 1969).
[19] J.A. Arnaud, "Apparatus for locating and measuring the beam waist radius of a Gaussian laser beam", Patent United States No. 3617755A (11 Febr., 1971).
[20] E.H.A. Granneman, and M.J. van der Wiel, "Laser beam waist determination by means of multiphoton ionization", Rev. Sci. Instrum. **46**, 332 (1975). https://doi.org/10.1063/1.1134202
[21] Y. Suzaki, and A. Tachibana, "Measurement of the Gaussian laser beam divergence," Appl. Opt. **16**, 1481 (1975). https://doi.org/10.1364/AO.16.001481
[22] G.N, Vinokurov, V.A. Gorbunov, V.P. Dyatlov, V.N. Sizov, and A.D. Starikov, "Method for the determination of the position of the focal plane of converging laser beams", Soviet Journal of Quantum Electronics, **6**, 364 (1976). https://doi.org/10.1070/QE1976v006n03ABEH011092
[23] E. Stijns, "Measuring the spot size of a Gaussian beam with an oscillating wire", IEEE J. Quantum Electron. **QE-16**, 1298 (1980). https://doi.org/10.1109/JQE.1980.1070431
[24] Y.C. Kiang, and R.W. Lang, "Measuring focused Gaussian beam spot sizes: a practical method", Appl. Opt., **22**, 1296 (1983). https://doi.org/10.1364/AO.22.001296
[25] J.T. Luxon, D.E. Parker, and J. Karkheck, "Waist location and Rayleigh range for higher-order mode laser beams", Appl. Opt. **23**, 2088 (1984). https://doi.org/10.1364/AO.22.001296
[26] S. Nemoto, "Determination of waist parameters of a Gaussian beam", Appl. Opt. **25**, 3859 (1986). https://doi.org/10.1364/AO.25.003859
[27] S. Nemoto, "Waist shift of a Gaussian beam by plane dielectric interfaces", Appl. Opt. **27**, 1833 (1988). https://doi.org/10.1364/AO.27.001833
[28] P.D. Gupta, and S. Bhargava, "An experiment with Gaussian laser beam", Am. J. Phys. **56**, 563 (1988). https://doi.org/10.1119/1.15555
[29] S. Nemoto, "Waist shift of a Gaussian beam by a dielectric plate", Appl. Opt. **28**, 1643 (1989). https://doi.org/10.1364/AO.28.001643
[30] P.B. Chipple, "Beam waist and M2 measurement using a finite slit", Opt. Eng. **33**, 461 (1994). https://doi.org/10.1117/12.169739
[31] C.R.C. Wang, C.C. Hsu, W.Y. Liu, W.C. Tsai, and W.B. Tzeng, "Determination of laser beam waist using photoionization time-of-flight", Rev. Sci. Instrum. **65**, 2776 (1994). https://doi.org/10.1063/1.1144615
[32] J. P. Landry, "*Optical oblique-incidence reflectivity difference microscopy: Application to label-free detection of reactions in biomolecular microarrays*, (University of California, Davis 2008).
[33] J. Wang and J. P. Barton, "Actual focal length of a symmetric biconvex microlens and its application in determining the transmitted beam waist position", Appl. Opt. **49**, 5828 (2010). https://doi.org/10.1364/AO.49.005828

[34] A.B. Ortega, M.L.A. Carrasco, J.A.D. Pintle, M.M.M. Otero, and M.D.I. Castillo, "New method to characterize Gaussian beams", Proc. SPIE, **8011**, in: *22nd Congress of the International Commission for Optics: Light for the Development of the World, 80114X* (2011). https://doi.org/10.1117/12.902192
[35] Y. You, J. Urakawa, A. Rawankar, A. Aryshev, H. Shimizu, Y. Honda, L. Yan, W. Huang, and C. Tang, "Measurement of beam waist for an optical cavity based on Gouy phase", Nuclear Instruments and Methods in Physics Research Section A, **694**, 6 (2012). https://doi.org/10.1016/j.nima.2012.07.022
[36] E.A. Bibikova, N. Al-wassiti, and N.D. Kundikova, Diffraction of a Gaussian beam near the beam waist, J. Eur. Opt. Soc.-Rapid Publ. **15**, 17 (2019). https://doi.org/10.1186/s41476-019-0113-4
[37] ISO 11146-1:2021 "Lasers and laser-related equipment: – Test methods for laser beam widths, divergence angles and beam propagation ratios – Part 1: Stigmatic and simple astigmatic beams". https://www.iso.org/obp/ui/#iso:std:iso:11146:-1:ed-2:v1:en
[38] ISO 11146-2:2021 "Lasers and laser-related equipment: – Test methods for laser beam widths, divergence angles and beam propagation ratios – Part 2: General astigmatic beams". https://www.iso.org/obp/ui/#iso:std:iso:11146:-2:ed-2:v1:en
[39] ISO/TR 11146-3:2004 "Lasers and laser-related equipment: – Test methods for laser beam widths, divergence angles and beam propagation ratios – Part 3: Intrinsic and geometrical laser beam classification, propagation and details of test methods". https://www.iso.org/obp/ui/#iso:std:iso:tr:11146:-3:ed-1:v1:en
[40] M.F. Malikov*, Fundamentals of metrology*, (Kommerpribor Publishing House, Moscow, 1949).
[41] G.A. Zimokosov, and K.I. Muntean, "Method for determining the beam waist coordinate of an optical quantum generator", USSR Author's Certificate No. 550917 (31 Oct. 1975).

ІНТЕРФЕРОМЕТРИЧНИЙ МЕТОД ВИЗНАЧЕННЯ ПОЛОЖЕННЯ ПЕРЕТЯЖКИ ПУЧКА ЛАЗЕРНОГО ВИПРОМІНЮВАННЯ

Вячеслав О. Маслов, Костянтин І. Мунтян
Харківський національний університет імені В.Н. Каразіна, майдан Свободи, 4, Харків, Україна, 61022

Розроблено інтерферометричний метод визначення місця перетяжки пучка лазерного випромінювання, що реалізує залежність кривизни хвильового фронту від його відстані до перетяжки. Вихідний лазерний пучок, розташування перетяжки якого необхідно визначити, розщеплюється інтерферометром зсуву на опорний та інформаційний пучки, що утворюють у відбитому світлі нелокалізоване в просторі інтерференційне поле. Період інтерференційних смуг, що спостерігаються в будь-якому перерізі інтерференційного поля, несе інформацію про місцезнаходження перетяжки вихідного лазерного пучка щодо цього перерізу. Відстань від перетяжки до площини реєстрації періоду інтерференційної картини обчислюється за формулами гаусової оптики. Принципова відмінність цього метода від відомих нині дозволяє підвищити точність отриманого результату за одночасного зниження трудомісткості процесу виміру.

Ключові слова: *лазер; гауссів пучок; розташування перетяжки; кривизна хвильового фронту; інтерферометр зсуву; двопроменева інтерференція; період інтерференційної картини*