SINGLE PHOTON BEAM AS A TOOL FOR MEASURING MICRO- AND NANOOBJECTS

Ryszard JABLONSKI

Warsaw University of Technology, Faculty of Mechatronics, Sw. A. Boboli 8, 02-525 Warsaw, Poland,
yabu@mchtr.pw.edu.pl

Abstract:

Until now, nobody succeeded in forming algorithm describing photon beam incident on the surface at 90 deg (sliding light). Due to the importance of this problem, we decided to solve it experimentally. The experiments started with measurement of extremely long microbores with focused laser microbeam. In the second stage of experiments we designed a simple model of Photon Batching Device (PBD) generating photon beam within the range from a few tens of photons up to several millions photons per second. At this level the corpuscular character of light dominates over its wave character. In the experiments an adjustable microbore was used (3mm long and 100μm in diameter). The outgoing energy, for particular microbore, was determined by scanning linearly and angularly the bore with photon beam and integrating the results.

The application of PBD has been extended to the measurement of microgaps formed of silicon samples of different slot thickness (100-500μm) and width (0-3μm).

Finally, a new experimental setup was designed according to the schematic of Mach-Zender interferometer. One of the mirrors is fixed to piezoceramics and oscillating at the frequency 20kHz. The intensity of signal beam I_s and heterodyne beam I_h were regulated independently over wide limits by attenuators.

In experiments, it was studied the influence of the aperture size on the beating signal with the equal power of I_h and I_s signals (the calibrated diaphragms had diameters 500, 50, 10 and 5 μm). Photons penetrate the opening 5 μm, it means that their transverse size is less than 5 μm.

Keywords: measurement, microelements, photon size, heterodyning, single photon

1. INTRODUCTION

The behaviour of low intensity photon beam penetrating micro- and nanoelements, such as: very small bores, gaps, slits, fibres, cylinders,.. is very difficult to define. Besides interference, the preferred measurement techniques are based mostly on light scattering or reflection, often when the photon beam ancients on the surface at the angle close to 90 deg (sliding light). Until now, nobody succeeded in forming satisfactory algorithm.

Due to the importance of this problem, we decided to solve it experimentally. The experiments started with measurement of extremely long microbores with the laser beam. In [1] the properties (power loss and phase distortion) of focused laser microbeam penetrating extremely long through microbores are described. The samples were prepared of glass-resin laminate with microbore diameter ranging from 35μm to 200μm and coaxially arranged in stacks.

The measurement information contained in laser microbeam penetrating microbore/microgap was too distorted to allow the extraction of measuring information from the signal; consequently we proposed an alternative method based on photon counting.

Theoretically it is possible to generate amplitude squeezed light up to the level of single photon beam, propagating straight in required direction. There are several proposals of photon cannons or stable sources of single photon. In principle these devices can generate single photon pulses, but to obtain stable periodical single photon generation of high directional stability is still too difficult.

With investigation of the light beams of extreme small intensities (so called of "single photon process") the new interesting effects are experimentally discovered, not always having clear physical interpretation.

As is known, Einstein, explained existence of photoelectric threshold by quantization the light beam, i.e., by splitting it into the separate wave packets of energy E determined from the frequency of wave ν: E = hν (subsequently they were named photons). The dimensions of this packet were not a subject of discussion. Further the model of photon as wave packet was successfully developed by Copenhagen school headed by Nils Bohr. These works showed that the probable shape of the envelope of wave packet (photon) is an ellipsoid, with transverse size somewhat less than λ, and longitudinal - somewhat more (see, for example [2]).

Experimental investigations of single photons were at that time practically impossible. All works were realized with comparatively large intensities of the light beams and furthermore monochromatic.

Until now this model frequently is used just in that form. However, it was explained that it does not give the possibility to interpret "single photon" phenomenon. In this connection the attempts to somewhat modify Bohr's model were made [3] and unfortunately this modified model also did not give the possibility to convincingly explain effects observed in "single photon" interferometric experiments.

With the large light intensities, in the classical representation of light waves, the process of heterodyning is intelligible. With the propagation in the linear medium the beams do not interact between themselves, both preserve

their structures even if they overlap in the space and in the time. However, the fields of these beams linearly interfere, being summarized in the places of overlap. If the directions of propagation of beams and space location coincide, then as a result interference causes the amplitude modulation of combined traveling wave. The modulation frequency is equal to a difference in the frequencies of the waves of initial beams. When this wave reaches quadratic photoreceiver, at its output the signal of beatings of this frequency difference appears. It is clear that the appearance of beatings during heterodyning is the purely interference process, which is possible only during the superposition of the waves of different frequency.

2. Photon batching device

Instead on stable source of single photon, it was decided an alternative method based on simple model of Photon Batching Device (PBD) generating photon beam of about 10^{-20}W. At this level the corpuscular character of light dominates over its wave character.

Out of many possible methods of reducing power of light beam, the following four were analyzed: (1) step attenuator (package of absorbing filters), (2) set of pinholes, (3) polarizing method, (4) forward current control of the light source. Finally the combination of 2 pinholes was chosen (this set-up does not reemit photons in infrared region). Attenuator reduces light power about 10^{17} times and the generated photon beam can be considered as "amplitude squeezed light". The scheme of the optical system is shown in Fig. 1. Its geometry is defined by:

p_0 - light source (LD), d_0 - light beam diameter, p_1, p_2 - pinholes, p_3 - diaphragm (entrance pupil of photo cathode), l_0, l_1, l_2, z - distances (as shown on figure), d_0 - LD beam diameter, d_1, d_2 - pinhole diameters, d_3 - exit pupil (aperture) of photo cathode diameter, d_4 - entrance pupil of PMT diameter, $E_0 \div E_3$ - photon field amplitude in respective part of PBD, E_4 - photon field amplitude on the photo cathode of the detector. Coordinate z is coaxial with the photon beam.
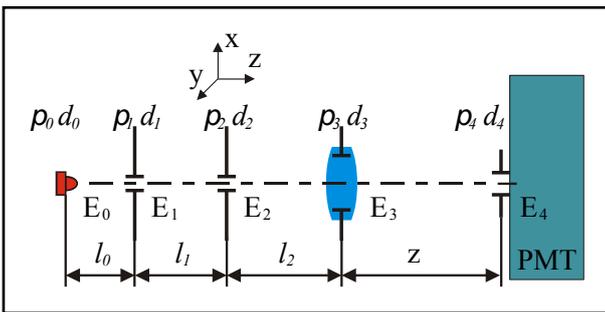

Fig.1. The scheme of PBD optical system
Laser, attenuator and beam forming optics (Fig.1) form a photon generator producing the batches of photons. In experiments, this PBD is fixed on slide table, which realizes movement in z direction with resolution 20μm.
The detector (PMT) moves in xy plane, scanning the beam transversely. The movement is realized by two microstates. The space around the generated photon field (enclosing PBD and PMT) is carefully sealed by and can be treated as

black chamber [4]. PBD batches the number of photons within the range 10 (min.) and $1,2 \cdot 10^6$ (max.), the forward currant operational range is $0 \div 45$mA and is divided into 256 levels. The mode of operation (continuous or pulsed with given frequency) and the value of current are set and controlled by computer.

2.1 Beam cross section

As a beam size, the diameter of circle containing 200 photons was assumed. For this value the coefficient of variation is about 7%. There is a slight ellipticity of the beam shape recorded. The observed oscillations are the result of aberrations of optical system and of reflection on 3D apertures. The diameters are $\phi_x=1,8$ and $\phi_y=1,9$mm. This maximum is present for any current level.

2.2 Time dependent photon distribution

Counting cycle can be adjusted within the range 0.001s to 1s. Fig.2 presents the distribution of counts in 0.16 s pulses with sampling time 0,0032 s. The standard deviation is 6,0
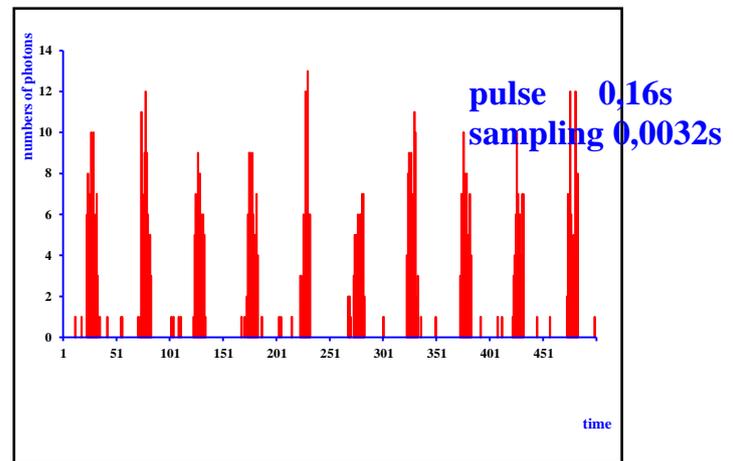
and mean value 65,5 of pulse's integration.
Fig.2. Photon distribution for pulses 0.16s and sampling time 0,0032s

The designed PBD was used as the light source in subsequent experiments. We assumed, that in photon counting based measurements a well-defined input signal (in terms of phonon number) will be advantageous.

Photon counting is an effective technique used to detect very low level light. It is accomplished by means of specially designed detector (Photon Counter) based on photomultiplier tube (PMT).

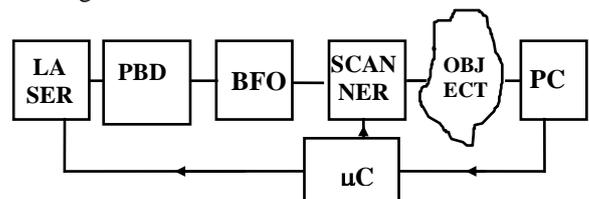The diagram of photon beam based measuring system is shown in Fig.3

Fig. 3. The diagram of measuring system

LASER output is reduced to photon level in PBD, shaped by Beam Forming Optics (BFO) and directed by SCANNER on the on the OBJECT. The measuring signal (in number of photons) is detected by Photon Counter PC. All the operations are controlled by microcomputer µC.

Laser scanner, described in details in [2], enables to direct shaped photon beam precisely on the chosen place of the object at the required angle. The angular accuracy can be 0.4'

3. Microgap

Since the official definition of microgap does not exist (conventionally it is assumed to be of a size less than 100µm, of any depths, length and shape) - a special samples were prepared. Also special housing enclosing PBD, gap slit gauge (sample) and PC was designed and realized. This housing meets all requirements of dark encapsulation.

Each sample consists of two silicon plates: one of them is in the shape of Johnson's type angular block gauge with one angle 40 arcsec (nominally) and the second one is rectangular. The plates adhere each other on their lateral sides, as shown in Fig.4, and the inclination of the first plate forms wedge (slot) with the other one. The volume of the wedge is treated as measurement object. The dimensions of both plates are also shown on Fig.4. Three samples thickness has been used: 0,1; 0,35 and 0,5 mm.
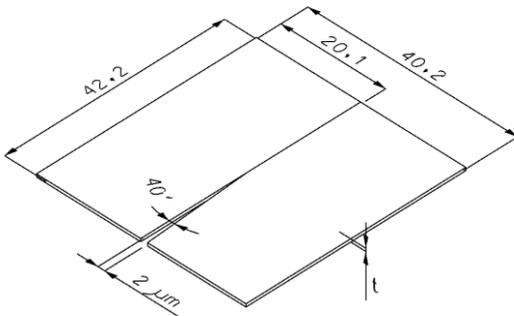

Fig. 4. The set of adhered silicon plates forming a wedge slot.

Transmission efficiency is understood as a relation between outgoing and incoming light energy. As the energy was normalized in time, in practice the light power (in number of photons) has been measured. Outgoing power, for particular slot width, was determined by scanning the slot transversely and angularly with laser beam and integrating the results.

The slot width was determined from triangle arisen by wedge edges, using optical measuring microscope (prior to measurement). The He-Ne laser was used as a light source. Experiment was performed in the darkroom with background 5 – 10 photons/second (including dark current of photomultiplier).

The series of experiment was carried out for on each sample. The obtained results of the dependence of light transmittance versus slot width and sample thickness are shown in Fig.5. The characteristic of efficiency versus slot width is non-linear in the width range between $(1,5\pm0,1)$µm and $(1,8\pm0,1)$µm.
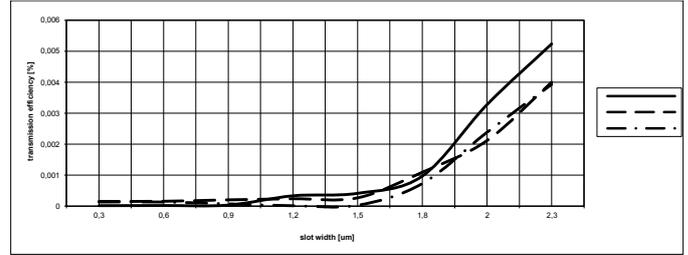

Fig.5. The efficiency of light transmission vs. slot width, for sample thickness range 0,1 - 0,5 mm.

Dependency between transmission efficiency and sample thickness is minute in the investigated range (0,1mm to 0,5mm). The transmission efficiency for the slots width less than 1µm is low, but possible to measure.

5. Microbores

The preliminary experiments with microbores were continued with the master of adjustable microbore formed of mutually accurately adjusted stack of metal plates, each 0,1 mm thick.

The measurement stand is analogous to the scheme presented in Fig.3, where master is an object.

Fig.6 shows the exemplary transmission efficiency for a lens-like shape of microbore radial section obtained with the master vs. form deviation represented.
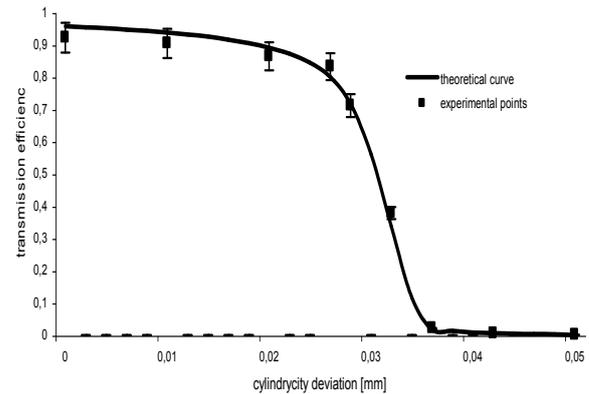

Fig 6. Light transmission efficiency vs. form deviation. Microbore diameter - 100µm, length – 2mm, axial section shape - arc with various radiuses. Photon beam divergence 0,1 mrad

Three main sources of uncertainty are considered:

1. Master performance uncertainty (does not exceed $\pm2,5$µm). It consists of stack performance uncertainty estimated as 1µm and single microbore plate position uncertainty 2µm.
2. Master set up uncertainty (does not exceed 1µm).
3. Light power uncertainty. The incoming light power fluctuation is 10%, it was proved that outgoing light power uncertainty is also 10%.

6. Photon diameter

The considerations concerns a study on the basic special features of the process of the appearance of beatings during

heterodyning of two laser beams of small intensity, which are differed in the frequency.

An experimental setup is designed according to the schematic of Mach-Zender interferometer (Fig.7). As the source of light was used the HeNe laser (λ =6328 nm) with a power of 4 mW. One of the mirrors is fixed to piezoceramics and oscillating at the frequency 20kHz. The intensity of signal beam Is and heterodyne beam Ih were regulated independently over wide limits by attenuators. The PMT signal was recorded with the two-channel oscilloscope equipped with digital memory and printer.
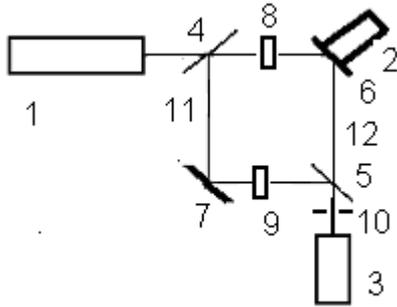

Fig.7. Optical scheme of measuring set-up.
1 – He-Ne laser, 6,7 – mirrors, 4,5 – beam splitters, 10 - aperture, 3 – photomultiplier (PMT), 8,9 – beam attenuators (polarizers), 2 – piezoceramic, 11 and 12 - signal (Is) and heterodyne (Ih) photon beams.

In the first series of experiments it was investigated the statistics of single photon pulses at the output of photomultiplier. The intensity of both beams was set equal. The total number of recorded photons (pulses) was on the average 25 in one period of the frequency difference, i.e. 5 10^5 pulse/s (quantum efficiency was not considered), which corresponds to the distance between the photons ~ 10^3 m. If beams 11 and 12 are directed to PMT by turns, then the distribution of single photon pulses at the output has random nature. But if to PMT are directed both beams, then statistics changes fundamentally. The periodicity of groups coincides with the period of the oscillations of mirror (Fig.1). The results of experiment clearly show that the interference of photons occurs even when the distance between them considerably exceeds λ.

In the second series of experiments it was studied the influence of the size of aperture 10 (Fig.7) on the beating signal with the equal power of 11 and 12 signals. The calibrated apertures had diameters 500, 50, 10 and 5 μm. With a change of the aperture the total intensity of incident light was adjusted by attenuators (polarizers) in such a way that the power passing through the aperture remained unchanged. It was controlled by measuring the number of pulses per second, recorded by PMT.

Photons penetrate the aperture 5 μm, it means that their transverse size is less than 5 μm. If the size of aperture exceeds 50μm, than the amplitude of signal beatings practically does not change. However with the diaphragm 5μm the amplitude of beating is smaller approximately 15

times comparing to the signal amplitude obtained with larger apertures (with the same power of the light passing through the aperture).

7. Conclusions

This effect is determined by the transverse size of photon. If photon passes the aperture without interaction with opening's boundaries, then the aperture does not influence on it (electrical and magnetic fields of the aperture material does not influence the photon and it is a possibility of the realization of the heterodyning process). However, if photon interacts with the wall of opening, then elastic scattering take place, i.e., the absorption of photon and the subsequent emission of other photon. The emitted photon has the same energy, but somewhat other direction of propagation and phase. This process is subjected to diffraction of photon on the border. The resulting divergence in the direction and/or in the phase of the photons makes them unable to interfere with themselves and gives the contribution to the signal of beatings. The number of photons freely passing through the aperture, is proportional to the area (square of the diameter). At the same time the number of photons, interacting with the wall, is proportional to the diameter of aperture. Therefore the influence of such photons on the process of interference diminishes linearly with the decrease of diameter. This dependence of signal on diameter gives the possibility to estimate the transverse size of photon. The carried out estimation showed that the probable diameter of photon is not more than 1-2 μm. This transverse size coincides with the commonly accepted value and the results of the experiments [3].

The heterodyne interferometer seems to be very promising also for the determination of real photon length. It indicates the importance of further both experimental and theoretical analysis on the formulation of the clear physical model of photon.

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