Automatized analysis of interferometric measurements on nanosecond pulsed discharge in liquid water

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Introduction

Fundamental physics of the discharge development in dielectric liquids is still a subject of controversy. While the modern plasma physical concepts describe phenomena in low-temperature gas-discharges with relatively high precision: from microscopic charge multiplication by electron avalanching to macroscopic parameters such as temperature, this is not the case for discharges in liquid phase. The crucial problems of primary electron multiplication in bubble-free liquid, picosecond timescales conditioned by molecular density, and dielectric properties of polar water molecules exposed to fast changing external electric field, constitute permanent challenges for physicists. One of the method to experimentally reveal the fast micro-physics taking place in mentioned discharges is the Mach-Zehnder interferometry for evaluation of changes in refractive index of studied media. This can be further used to estimate the pressure or electric field distribution which is generated by the nanosecond high-voltage pulse applied onto the metal electrode inserted in the water.

Experimental setup

For pressure field detection, Mach–Zehnder interferometer was used. Uncovered glass cuvette is filled by conductive water solution with immersed high voltage electrode with sharpened tip. The sharpened electrode has diameter of 35 μm. The pulsed power supply was used up to 50kV. As a source of coherent radiation for production of interferogram, the pulsed laser (Elforlight, SPOT-10-200-532) with wavelength of 532 nm was used. Produced pulses have energy of 6.2 μJ/1.76 ns at maximum repetition rate of $5 \cdot 10^{-4}$ s^{-1}.

Interferogram analysis

Optical interferometry is based on interference of measuring and reference light rays. The phase of measuring rays is shifted as a result of propagation through a regions with different refractive indexes. The interference of measuring and reference light rays leads to interference pattern. Any present inhomogeneity in the path of measuring ray results in shift of fringes, which can be used to determine phase shift along its path.

The refractive index of undisturbed region n_0 and refractive index of present inhomogeneity n results in phase shift δS which can be determined as:

$$\delta S = \frac{\delta n dx}{\lambda}, \tag{1}$$

where δn represents difference of n and n_0, dx expresses distance where δS emerges and λ is wavenumber of propagating light ray.

In case of spherical or cylindrical symmetry of inhomogeneity, it is possible to use onion-peeling method to determine the behavior of δn in concerned inhomogeneity. The method is based on the division of inhomogeneity to the series of co-centric layers. By iterative procedure from the outer to the inner layer, the refractive index can be calculated. The process of evaluation can be expressed as:

$$\delta n_k = \frac{\delta S_k \lambda - \delta n_1 d_{1,k} - ... - \delta n_k d_{k-1,k}}{d_{k,k}}, \tag{2}$$

where k represents number of layer with δn_k, δS_k and distance between layers $d_{k,k}$.

With the information about deviations of refractive index inside inhomogeneity, it is possible to determine liquid density by Lorentz-Lorenz formula:

$$\frac{n^2-1}{n^2+2} = \frac{4\pi\alpha N_A}{3M}\rho, \tag{3}$$

where α represents liquid polarizability, N_A is Avogadro constant and M is the liquid molar mass.

In case the deviation of liquid density $\delta\rho$ is positive then Tait's equation is used to determine liquid pressure (4). In the opposite case, the linear approximation by water bulk modulus K of liquid pressure can be assumed (5).

$$\frac{p+A_w}{p_0+A_w} = \left(\frac{\rho}{\rho_0}\right)^c, \tag{4}$$

$$\delta p \approx \frac{K}{\rho_S}\delta\rho, \tag{5}$$

where ρ_S is liquid density at normal pressure.

Automatization of analysis of interferometers

To achieve automatization of δn(x), ρ(x) and p(x) determination, the scripts in Python are created [1, 2, 3]. An example of interferogram is displayed in fig. 1a for illustrative purposes. Firstly, for the individual columns of interferogram are located maxima to isolate constructive interference pattern. To correctly calculate phase shift of measuring ray I(x) from reference ray I_0(x), the ability to differentiate between specific light rays is pivotal, see fig. 1b. To determine radial profile of δn, one specific vector is selected. The vector is intersecting the center of curvature and propagates parallel to light rays, see fig. 2a. The phase shift δS is determined as intensity of measuring ray $I(\mathrm{x})$ divided by the mean value of intensity of reference ray I_0. Nevertheless, when selected vector propagates closer to the centre of curvature it has to be taken into account that shift by one fringe is causing additional phase shift of $\delta S = 1$.

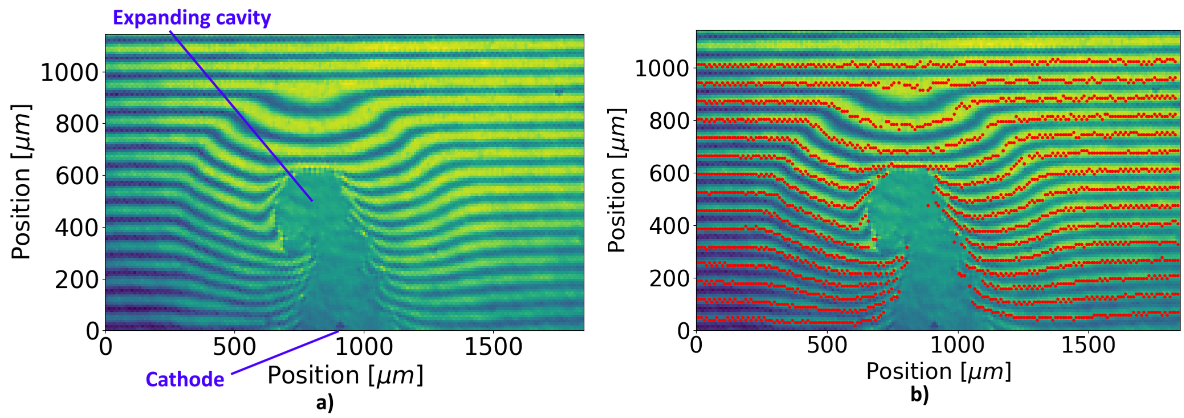

Figure 1: An example of interferogram for illustrative purposes with **a)** interpretation of its crucial elements , **b)** differentiated individual light rays. Original interferogram is taken from [4].

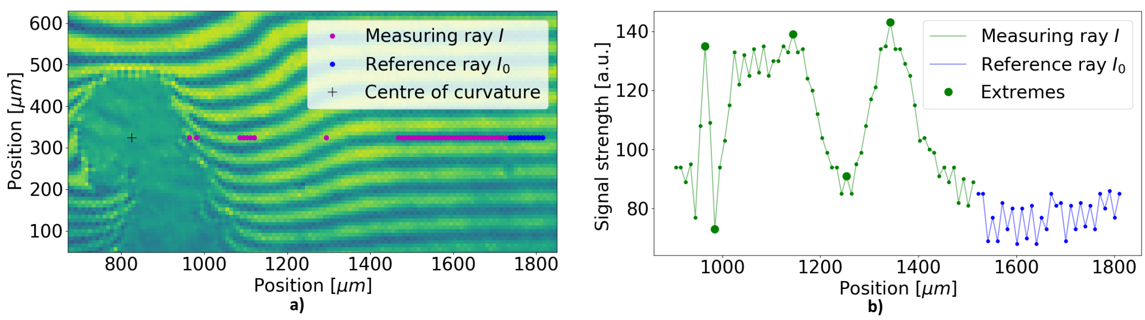

Figure 2: **a)** Vector used for determination of δS radial profile, **b)** intensity of selected vector in dependence on position with highlighted extremes used for further calculation.

Intensity of vector displayed in fig. 2a is plotted in dependence on its position in interferogram and extremes are determined, see 2b. The intensities of extremes are divided by the mean value of intensity of reference ray and additional phase shift is added in dependence on number of fringe shifts (shift by 2π represents $\delta S = 1$, shift by π represents $\delta S = 0.5$). To determine number of fringes shifts for specific extreme, the behavior of light rays corresponding to maxima is analysed. In other words: the light ray that includes analysed maximum is selected and is monitored if the intensity of light ray is rising, dropping or stagnating in close vicinity of maximum. If the intensities in proximity of extremes are nearly constant, the closest points with lowest deviation of intensity are selected for increased precision.

With the information about distance of analysed point from the center of curvature $d_{k,k}$ and its phase shift δS_k, the deviation of refractive index δn_k is determined, see fig. 3a. For the calculation was used equation (2). From the dependency of δn_k on $d_{k,k}$, the density ρ and pressure p is determined by equation (3), (4) and (5). The resulting pressure p and density ρ are displayed in fig. 3b.

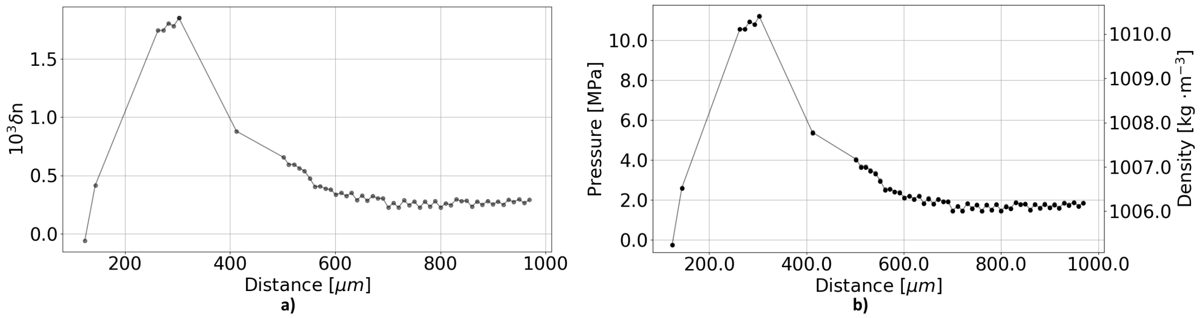

Figure 3: **a)** The deviation of refractive index δn in dependence on distance x from the center of curvature, **b)** the dependency of pressure p and density ρ on the distance from the center of curvature.

Summary

To achieve automatized analysis of interferometric measurements, the series of scripts were created. Resulting values of δn, ρ and p have only small deviations of expected values due to the noise of interferograms. Precision of constructive interference pattern detection is also heavily affected by noise in interferograms and can considerably affect resulting values. For this reason the use of soothing algorithm would be beneficial. Another improvement of results precision would be achievable by considering more points in inhomogeneity, not only extremes. The implementation of both improvements is planned in the future.

Bibliography

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