Phase-Sensitive Optical Coherence Microscopy of Integrated Nanophotonics Devices

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Abstract. We report on the development of a new approach for studying the internal structure of polymer integrated nanophotonics devices using phase-sensitive optical coherence microscopy. Visualization and flaw detection of devices and their internal structure was carried out using the example of coupling gratings and prisms for a miniature Otto configuration with a characteristic gap height of 50-300 nm.

INTRODUCTION

Optical coherence microscopy (OCM) is a method of optical interferometry, which makes possible three-dimensional visualization of micro-objects. OCM is based on a combination of optical coherence tomography (OCT) and confocal microscopy [1]. OCM allows three-dimensional mapping of the refractive index of the sample and has a submicron resolution [2]. In addition, one of the methods, phase-sensitive OCM, has subnanometer axial sensitivity to changes in optical path-length [3]. The submicron resolution of the OCM makes it a powerful tool for studying semitransparent objects.

One of the areas of application of the OCM in recent years is flaw detection of microscopic devices and chips. OCM makes it possible to non-invasively study the internal structure of semitransparent objects, and therefore it can be used to search for defects in various polymer and crystalline structures without destroying them and allowing further use of the tested device. The method is already being used to study microscopic photonics and fiber optics devices [4].

The advantage of the method is its non-invasiveness and the ability to visualize the internal structure of semitransparent objects, which is important for flaw detection of integrated nanophotonics devices with a complex internal structure.

Our goal was to apply phase-sensitive OCM to study semitransparent polymer integrated nanophotonics devices fabricated by femtosecond laser polymerisation technique [5]: both for relatively simple devices and for devices with complex geometry and internal structure.

METHODS

Phase-sensitive OCM is based on the interference between two beams: reflected from the sample layer with intensity reflectance \( R_s \) located at a distance \( z_s \) from the beam splitter, and reflected from a reference mirror with reflectance \( R_r \) located at a distance \( z_r \) from the beam splitter. In our version of the method, the interference fringes appear on a wide spectrum (\( \Delta \lambda = 300 \text{ nm} \)) of the source depending on the wave vector \( k \) (Fig. 1).

Samples such as polymer microprisms and other integrated nanophotonics devices usually consist of several layers, differing in refractive index. Let’s consider a device with two layers, the refractive indices of which are \( n_1 \) and \( n_2 \). At the boundary of these layers with coordinates \( z_{s1} \) and \( z_{s2} \), reflection occurs (\( R_{s1} \) and \( R_{s2} \)).

Let us denote the thickness of the layer with the refractive index \( n_1 \) as \( d \). As a result of the interference of rays reflected from the boundaries of the layer with the ray reflected from the reference mirror, characteristic interference fringes appear on a wide spectrum of the source. Then, from this interference pattern, using the Fourier transform, it is possible to extract the optical path that the ray travels in this layer, and from there — the layer thickness: \( d = n_1 = \frac{\lambda_0 \Delta \psi}{4\pi} \), where \( \Delta \psi \) is the change in the Fourier phase when the ray passes through the layer with \( n_1 \), \( \lambda_0 \) is the center wavelength of the source. A polymer prism printed on a substrate (Fig. 2) or a gap between the prism and the substrate (Fig. 3) can act as such a layer.
FIGURE 1. Schematic diagram of the phase-sensitive OCM method used for visualization of integrated nanophotonics devices.

A similar method is used to study the structure of biological cells [3]. However, the method was first used to study the internal structure of polymer integrated nanophotonics devices.

RESULTS AND DISCUSSION

At the beginning, we investigated polymer microprisms — prototypes of gratings for coupling surface electromagnetic waves on photonic chip with incident free-space radiation [5]. Figure 2 shows a comparison of images of a micro prism obtained using an optical microscope (a), as well as using a phase-sensitive OCM — a scattering intensity map (b) and an optical path-length difference converted to heights (c).

Figure 2 clearly shows that the phase-sensitive OCM made it possible to determine the geometric dimensions of the prism, including its height (200 nm), which is difficult to do using conventional optical microscopy and other non-invasive methods, after which the object can be used.

FIGURE 2. Image of a polymer micro prism under an optical microscope (a) and its OCM scan: scattering intensity map (b) and an optical path-length difference converted to height (c). The bar represents 5 µm.

The next object of our study was miniature Otto configuration [6] devices, which have complex internal structure. These devices are more efficient and able to couple normally incident radiation. The prisms use the Otto scheme: excitation of a Bloch surface wave through a gap between the prism and the substrate of the order of 100 nm. The height and shape of the gap have a significant impact on the efficiency of coupling. The problems of studying the gaps are their small heights and their location inside the structure, which does not allow the use of contact visualization methods and methods for which the prism is opaque. This problem can be successfully solved by optical interferometry.
Using the developed method for studying the gaps, we are able to determine the height of the gap in the prisms, depending on the manufacturing parameters (Fig. 3). The accuracy of determining the gap is up to 10 nm and varies depending on the print quality and the features of the prism shape. Figure 3 shows that the method makes it possible to reveal a linear dependence inherent in devices during manufacturing. In addition, the method also allows one to build a three-dimensional image of the gap — the dependence of the height on the transverse coordinates. These data can then be used in numerical simulations to explain the experimentally evaluated coupling efficiency and to determine the printing parameters that ensure the creation of the prism with the highest efficiency of the coupling.

CONCLUSION

Integrated nanophotonics devices are becoming more and more complex: devices with sophisticated internal geometry appear, for example, with gaps with a height of about 100 nm. Studying such devices, determining their characteristics, and detecting defects in them is important for predicting their optical properties and efficiency. However, there is a lack of non-invasive optical methods for studying such devices.

We proposed using the phase-sensitive OCM method for imaging and characterization of integrated nanophotonics devices, both relatively simple and devices with a complex internal structure. The method made it possible to construct images of objects and determine the geometric properties of the internal structure, which can be further used both for analyzing the efficiency of the device and for flaw detection.

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