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Review of the PhD dissertation entitled "Optical properties and development of flat-surface nanostructured gradient index micro-optical vortex phase components" by Mrs. Hue Thi Nguyen

The subject of the doctoral dissertation entitled "Optical properties and development of flat-surface nanostructured gradient index micro-optical vortex phase components" by Mrs. Hue Thi Nguyen is theoretical and experimental investigations of photonic phase masks that enable the generation of optical vortex beams. Such beams are characterized with an orbital angular momentum, providing the light with unique properties and hence enabling research ranging from optical (superresolution) microscopy to quantum optics (encoding quantum information in the orbital angular momentum). Typically, optical vortex beams are generated using bulk optical elements, e.g., phase plates with spiral phase retardation. Mrs. Nguyen worked on the problem of generation of the beams using an alternative approach that is based on two-dimensional photonic "crystals" (the word "crystal" is put in quotation marks due to the semiperiodic structure of fabricated elements). The appropriate distribution of hundreds or even thousands of inclusions in a material that has distinct optical properties (e.g., refractive index), while the introduced inclusions have dimensions comparable to propagating-light wavelength, leads to a spatial dependence of the refractive index of such an element. This approach enabled the Author fabrication of elements that were used for the generation of the optical vortex beams with a given topological charge.

The work of Nguyen consists of several parts. The first part, following the introduction, is devoted to the theoretical description of optical vortex beams and discussions of experimental techniques enabling characterization of the beams. Additionally, the part contains a short overview of possible applications of optical vortex beams. The Author dedicated a next section to the theoretical description of binary (two types of materials) photonic crystals that are grounds for the investigated phase masks. For that, Mrs. Nguyen introduced the effective medium theory, which later allowed her to simulate the phase masks, as well as technological requirements for materials used for fabrication of the elements. The theoretical aspects of the optical phase masks are further developed in the next section, describing simulations of the optical properties of the beams generated with designed phase masks. The final and to me the most important and authorial part of the work discusses the research on real structures used to produce vortex beams. This part not only presents studies of the fabricate phase masks but also

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describes their implementation in fiber microprobe and achromatic phase mask. The conclusions are gathered at the end of the dissertation.

The fabrication of phase masks is a multistage process. Motivated by its complexity, the Author presented the description offering better understanding of the research presented in the dissertation. The first stage of the process is design of appropriate structures of the optical element that realizes the specific task, i.e., generates beams with specific topological charges. To achieve this goal, Mrs. Nguyen used the simulated annealing method. This technique aims at minimizing the differences between the required phase profile of the element and the profile corresponding to a given arrangement of inclusions. Through implementing specific stochastic algorithms and by using the effective medium theory Mrs. Nguyen introduces an effective permittivity of the element. Based on the presented theoretical description, one may realize that the permittivity and hence global optical properties of the element depends only on the contrast of the refractive index and the fill factor. Although I understand this is being used in the field (it seems the technique is not being developed but just used by the Author), a question arises of **whether the sizes of the inclusions, in addition to the effective filling and phase contrast, have an impact of the generated refractive-index profile**. In fact, I missed such a discussion at work and would welcome such an analysis. A specific attempt toward realization of such a task would be a comparison of the theoretical result presented in the dissertation versus numerical simulations calculated by some other techniques (e.g., finite element method). The next stage in the fabrication process is to analyze the physical (not only optical) properties of the materials. This is so because the materials must not only have specific refractive indices but also their mechanical properties need to match. The key problem in this context is that the presence of stress could introduce birefringence and hence significantly modify the propagation conditions, but also, in extreme cases, may lead to destruction of the fabricated elements. During her thesis, Mrs. Nguyen analyzed several different glasses for generation of phase masks. This works allowed her to identify materials with desired properties. During reading of the part, the question of the effect of the role of the microstructure on propagation condition returns. While in the first place, the refractive-index-dispersion difference determines the properties of the light transmission, presence of the microstructure can introduce additional effects. This is a particular reason why one may fabricate an endlessly single-mode fiber using two-dimensional photonic crystal. My question then is **whether a similar propagation effect would not change the propagation condition in the fiber and then the refractive-index difference just the first approximation to the problem**. The last stage in the fabrication of phase masks is the construction of preforms used for the elements and their successive drawing. The amount of work put into the preparation and testing of photonic structures by Mrs. Nguyen is highly appreciated. Arranging over 7,000 glass rods with different refractive indices is extremely difficult and tedious work. The several dozen hours that the PhD student devoted to the preparation of the preforms reveals her reliability and diligence, i.e., skills needed for scientific work.

In her work, Mrs. Nguyen paid particular attention to numerical simulations of the designed structures as well as their experimental tests. In the first context, the Author used the beam-propagation method

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supported by the Fourier transform (expanding light into its spatial-mode basis). This allowed for an effective (relatively simple, yet not too time-consuming) calculations of parameters of the light propagating through the structure. In the dissertation, the approach was used to calculate both the intensity and phase character of the generated vortex beams.

One of the outcomes of the performed analysis was the demonstration of the existence of the so-called waveguiding effect. The effect consists of spatial localization of light within the phase mask. As a result, the symmetry of the intensity profile of the vortex beam is broken. The effect also modifies the phase profile of the beam. Throughout the studies, the waveguiding effect became one of the most serious limitations of the described approach. In the dissertation, the problem was addressed by manufacturing extremely thin optical elements in which the propagation of light has not yet reached a steady state. Unfortunately, the waveguiding effect was not studied in more detail in the dissertation, which would be interesting. I wonder if Mrs. Nguyen made an attempt to solve the problem in some other way than the one described in the dissertation. For example, photonic crystals offer many unique capabilities in engineering optical properties of fabricated elements. **Isn't it possible to utilize the approach to address the waveguiding problem?** Such a solution would be an elegant yet powerful method, opening means for several applications.

The last aspect of the dissertation is experimental research. For the research, the Author built at least two experimental systems: one to study optical-vortex beams (three variants of the same system are used in characterization of the beams) and second for integration of the phase masks with optical fibers (production of optical fiber probes). It should be noted that the experimental investigations were the key element of the final verification of the concept. Specifically, the Author experimentally verified the possibility of producing optical-vortex beams, including the beams with a topological charge equal to 2. These results are in good agreement with theoretical simulations, and some deviations of the observations from theoretical predictions may be related to either the limitations of technological processes or imperfections of the fabricated structures. The conducted research also confirmed the existence of the waveguiding effect, which stressed the necessity for its addressing in future work.

A natural extension of the experimental research on phase masks are studies on their applications. A particular example is the fiber microprobe produced through a combination of a single-mode fiber and a phase mask (for technical reasons they must be separated by a special distancing layer). By conducting numerical simulations and experimental tests, Mrs. Nguyen proved that the construction of such an element is possible, although due to the need to ensure appropriate coupling conditions, it is not an easy task. While I do understand that combination of the phase mask with a fiber is potentially interesting, I must confess that I somehow missed a specific example of where such a mask could be used. Therefore, I would appreciate **if the Author could offer a short discussion on the envision applications of the phase-mask fiber microprobe.**

Another example of extending the research on the phase masks is the creation of achromatic masks. Such masks are able to produce optical vortices with specific topological charges at two different

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wavelengths. This goal is achieved by using glasses with appropriately profiled dispersions. Specifically, the refractive indices of both glasses may be selected in such a way that their difference has identical values for two wavelengths (in the case described in the dissertation this occurred at 600 and 1000 nm). It should be noted that this work was purely theoretical, as Mrs. Nguyen did not manage to fabricate the achromatic masks due to the time constraints. Despite that it was not a complete project concluded with the experiment I would still like to come back to **the question of the effect of the microstructure for the dispersion**. In the particular case considered in the dissertation, two wavelengths differ by a factor of two, so principally the propagation conditions for these two light wavelengths may be different.

An important question that should be asked in the context of the presented work is the character of the research. Is it purely fundamental or is there a practical load on the work? I have already mentioned two applications discussed in the dissertation and some of the problems that are associated with the fabrication of phase masks. However, I would like to ask a question or, if interesting, offer a suggestion for further research. I wonder if this is possible to introduce metallic enclosures into the phase mask and/or explored electrooptical effects in the masks. If fabrication of such elements is possible, the ability to quickly switch the optical charge may be of extreme importance for many brands of modern optics, including quantum optics. Obviously, both fabrication of the wire-containing masks and the fundamental limitation due to introduction of metal elements into the structure (plasmonic effects?) may make the idea impossible to implement. On the other hand, however, if such elements may be fabricated (this would be a project beyond the reviewed dissertation, of course), they would find many important applications.

Finally, to prove that I carefully read the dissertation, let me mark some editorial errors of the presented document. The dissertation is not free of all kinds of minor errors. Some problems are absence of axis labels in Figure 3.6, incorrect reference to Figure 3.5(a) on page 32 (it should be Figure 3.8), the differentiation in equation (4.3) performed over x while it should be done over z, pages 68, 77 and 78 appear twice in the printed document (I wonder if these pages are missing in other works). Finally, as an "article-less" speaker, I am able to understand Mrs. Nguyen inability to put articles anytime they are needed. However, all these errors are relatively minor and do not make a negative impression about the work as a whole, which was prepared in a neat and careful manner.

One of the tasks of the reviewer is to assess the academic maturity and independence of the candidate of a PhD student. In this context, it is worth analyzing the bibliographic data of the Author. Mrs. Nguyen is a coauthor of nine peer-reviewed articles, out of which six constitute the basis for the doctoral dissertation, and in four of them Mrs. Nguyen is the first author. In addition, she is the coauthor of eight conference papers. This is a very good result for the student, showing the great commitment of Mrs. Nguyen and her maturity as the scientist.

In conclusion, the work presents interesting research that combines both fundamental and technical aspects of optics. It presents the extensive knowledge that Mrs. Nguyen acquired and developed during

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her PhD. The presented solutions are innovative and represent an important addition to the field. In this context, **I believe that the thesis meets all the formal and customary requirements for a PhD dissertation, and I request the admission of Mrs. Hue Thi Nguyen to further stages of the PhD defense.**

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