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Views

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Transferring diffractive optics from research to commercial applications: Part I – progress in the patent landscape

Abstract: In the last 20 years, diffractive optics experienced a strong research interest and was in the center of many development projects in applied optics. To offer a side view for optical engineers, here, we discuss selected, business-related aspects of the current status of the transfer process to bring diffractive optics into commercial products. The contribution is divided into two parts. Here, in part I, we focus on the patent landscape of diffractive optics with a closer look on the temporal development and the distribution over main players. As an important result, currently, new strong patent activities are observed especially in the context of imaging systems. In the second part, the business volumes of selected market segments are discussed.

Keywords: diffractive imaging optics; DOEs; patent strategies.

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1 Introduction

In the 1990s and in the beginning of the preceding decade, diffractive optics experienced a strong and widespread interest in the research of applied optics. At that time, the progress in theory, the development of new and adequate simulation tools, and also the improvements in the manufacturing technologies of diffractive optical elements (DOEs) opened up a broad spectrum of new applications and also allowed to improve the concepts of already existing setups. The application of diffractive optics expanded from the historical roots of spectroscopy to illumination systems, e.g., for beam-shaping, homogenization, coherence management. Finally, due to the extreme different dispersive characteristics of DOEs, compared to refractive lenses, they allow an advantageous combination of both to form hybrid imaging systems with optimized performance and compactness. To name a few, the imaging hybrid concept was applied to eyepieces [1–5], head-mounted displays (HMDs) [6–8], inspection systems for semiconductor manufacturing industry [9, 10] and also for new concepts of space telescopes [11, 12]. In this field, the activities of the Japanese company Canon attracted very high interest. Canon succeeded to transfer the hybrid concept to commercialized high-quality photo lens systems and achieved a reduction in length and weight by one-third compared to a classical dioptric system but still offers the same optical performance [13].

The research activities in diffractive optics of the 1990s and in the beginning of the new millennium were accompanied by various public grant programs, which were initiated to support the basic research work and also to push the new ideas to commercially exploitable technologies and prepare the transfer to new products. The specific interest in diffractive optics was also reflected by numerous technical conferences, which addressed theoretical, technological, and also application-oriented aspects of DOEs. Meanwhile, diffractive optics shifted slightly out of the central focus of the research activities of the optical community, and it seems that it became rather quiet around this topic.

In two contributions for this journal, we discuss some business-related aspects of the current status of diffractive optics. Especially, we want to highlight current commercial activities in the transfer of the original ideas in market-acceptable products. For this purpose, in essential, we address two major aspects. In part I, we discuss the patent activities on 'diffractive optics' over the last years. This allows to trace the temporal shift of the application focus of diffractive optics and also to take a glance at the patent strategies of important players in the market. Later, in part II, we compare different markets in which diffractive optical components are applied and are analyzing the market sizes and perspectives. The articles are mainly addressing optical engineers working in a scientific or technical background to offer them a side view on some business-related aspects. The articles do not have the claim of a reliable quantitative determination as a basis for a specific business model. In this contribution, in a preceding section, we also point out some general remarks on the challenges and difficulties, which are associated with the introduction of diffractive optics in ambitious optical systems.

2 Challenges in transferring research results of diffractive optics in commercial systems

Diffractive optical components have a large potential to improve a wide variety of optical systems ranging from spectroscopy and illumination systems up to imaging instruments. Especially in imaging systems, the use of diffractive optical elements allows system characteristics, which cannot be fulfilled by a classical dioptric approach. For example, the extreme different dispersive characteristics of DOEs, compared to refractive elements, offer more degrees of freedom in the lens design and allow an advantageous combination of both to form hybrid systems with optimized performance and compactness. Another beneficial characteristic of DOEs concern their wavelength selectivity, in which the diffractive surface addresses different diffraction orders for different wavelength so that an independent design optimization for both wavelengths is possible. Additionally, a tailoring of the profile form of imaging DOEs allows also multifocal options so that different distant objects can be imaged simultaneously in the same plane.

Despite all mentioned advantages, which DOEs offer, their transfer into commercial systems is still rather limited, and the question about the reasons for the moderate business success arises. To get closer to answers, both scientific-technical and business-related aspects have to be considered, where both influence each other.

From the scientific-technical point of view, a central challenge concerns the essential necessity to have a complete control over each step of the entire realization chain of the addressed optical instrument. The risk of a failure may depend on the missing of one single link.

This chain comprises, among others, the optical design of the system, the broad variety of manufacturing methods of the DOEs, the element testing, and the system integration, where each step differs significantly from processes applied in case of pure refractive systems.

A successful optical design of a sophisticated system is often related to the experience of the responsible engineer and does not follow simple procedures. Owing to the totally different properties of DOEs compared to classical lenses, e.g., their inverse chromatic behavior, the multifocus properties, or the wavelength selectivity, a change in approaching the optical design becomes indispensable, which sometimes leads to errors or to a complete failure and, thus, increases the development time. Additionally, apart from classical ray-trace and scalar diffraction theory, the optical designer of a hybrid system also needs extended knowledge in rigorous diffraction theory and has to be experienced in using methods such as rigorous coupled wave analysis (RCWA) or finite-difference time-domain (FDTD) methods.

The manufacturing technologies of DOEs are mainly divided into three categories: the mastering process, the manufacturing of the replication tool, and the replication process. For each of these categories, a large zoo of different technologies has been developed. For example, for the mastering process or for the manufacturing of a limited number of high-quality elements, technologies such as single-point diamond turning, ruling, direct laser beam writing, e-beam writing, interference lithography, mask projection lithography, or laser ablation are available today. To name a few more, injection molding, hot embossing, UV-curing, or glass precision molding are possible technologies for the replication process. Each of these technologies has certain advantages but also has its limitations so that they are only applicable for specific problems, and an 'all-purpose technology' is not available. Moreover, the introduction of several different technologies is expensive and time consuming so it is often economically not justifiable.

From the beginning of the introduction of a new system concept, such as the introduction of the hybrid concept in imaging optics, the related technology has to compete with well-established system concepts with continuous and well-approved process chains, in which every detail has been optimized over years and decades. The new system concept and the related necessary manufacturing processes have to overcome all these hurdles in one step. Especially, regarding commercial decisions, the exemplary demonstration of the new approach in a single demonstrator is often not sufficient, instead, the entire process chain has to be available. The gradual improvement of an established process is much easier and needs less expenditure of time than the introduction of a complete new technology. This leads to enormous persistence of an established 'working system'.

The persistence of conservative technologies was also observable when aspheres were introduced in photo lens systems. At that time, the manufacturing of perfect spherical surfaces was well-established, but the new aspheres showed aberrations so that the final aspherical system showed insufficient performances, and the potential advantages of the aspherical concept could not be accentuated. Yet, the manufacturing technologies of aspheres eventually made significant progresses, and finally, the commercial winners were those companies that had demonstrated perseverance in the new approach.

Nowadays, in many applications, DOEs have proven their enabling function, which means that the use of DOEs potentially allows a system performance that cannot be fulfilled with the established approach. Moreover, the price or cost of a single element of a system has to be, in general, in the same range as the one that is replaced. Customers are often not willing to pay significantly more for a new product than for the preceding one. When starting with a new technological approach, such as using diffractive optics for imaging the application, the capability is often limited to a few examples, so that only a limited number of elements will be needed. Consequently, the introduction of a new technology is expensive. The necessary investment in a new technology, the limited number of immediate product-applicable elements and often the low achievable price for a single element prevents the management from deciding in favor of the introduction of the new technology. Especially, this becomes difficult in profit center-organized manufacturing units, which have to work cost effective for almost every manufactured element. Here, a financial deficiency in the production of the elements, themselves, cannot be balanced by an economical success of the whole system or product.

Typically, the commercial success will become visible only after a period of several years, a time frame that sometimes exceeds the time horizon of the management. From these aspects, it follows that a market entry of a new innovative technology, such as the introduction of DOEs in optical instruments, will only be successful when the performance demand cannot be fulfilled in the classical conservative way.

3 Patent activities in the application environment of 'diffractive optics'

An appropriate indicator, which allows the estimation of the importance of selected topics for applied industrial research, is based on the observation of the corresponding patent activities. From the evaluation of the patent activities, certain properties such as quantitative efforts and partially, future strategies of the involved companies can be derived.

We applied this evaluation to the particular topic of 'diffractive optics' aiming at finding the current status and future trends. For a basic investigation, we used the patent data source 'WPINDEX' [14], which provides information on patent publications from more than 40 important patent-issuing authorities in the world. To obtain more specific results in our considerations, we excluded entries in which the term 'diffractive' is correlated to spectroscopic issues but concentrated on alternative topics such as technology and application of diffractive optics in the context of imaging and beam-shaping optics. As a starting point, we applied the search term 'Diffractive?' in combination with '(optic? or element? or device?)', and found approximately 2300 entries. On the one hand, the use of the mentioned data base, which is linked to several dozens of patent organizations, has the drawback that eventually also multiple entries of the same patent are counted, which has been published in different countries. On the other hand, with the approach of combined search terms, a number of relevant entries may be overlooked. It has to be mentioned that with our analysis, we do not target on exact total numbers but on qualitative aspects, which, for example, allow the estimation of dimensions, the temporal trends, as well as the classification of technological and application-oriented subjects.

The diagram in Figure 1 displays the quantity of published patents as a function of the publishing year (priority date). The time scale covers a period of 20 years from 1992 to 2012. The y-axis shows the number percentage per year related to the total sum of found patents. The diagram shows a continuous increase with a maximum

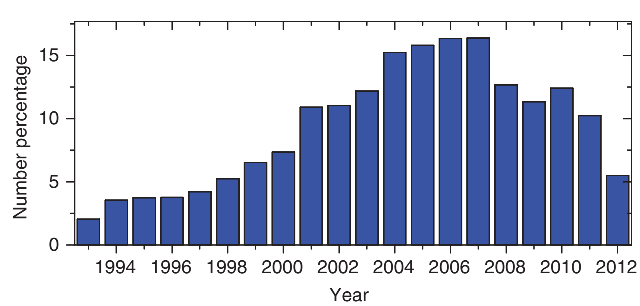

Figure 1 Overall patent activity in the field of 'diffractive optics'. The diagram shows the percentage of published patents dependent on the publishing year. Combining the search term 'Diffractive?' with '(optic? or element? or device?)' leads to approximately 2300 patents.

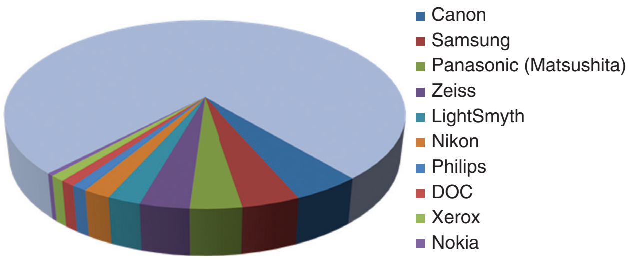

Figure 2 Landscape of published patents related to involved companies. Ten companies cover approximately 25% of all published patents. Seventy-five percent of the patents are distributed to players, which hold only a few or a single-digit number of patents.

number of published patents in the years 2006/2007. After this maximum, a significant decay can be observed in the overall patent activities.

Another basic categorization of the patent activities allows the attribution of the number of published patents to the involved companies (see Figure 2). Ten companies that hold the maximum number of patents in the addressed field, cover approximately 25% of all published patents. Seventy-five percent of the patents are distributed to companies or institutions that hold only a few or a single-digit number of patents. The Japanese company Canon was found to represent the largest share with 4.7% followed by Samsung (~4%), Panasonic/Matsushita (~3.5%), and Zeiss (~3.4%).

A more detailed view is obtained by investigating the publication date of the patents for different companies. Figure 3 shows the distribution of published patents for different selected companies over the years. The z-axis is normalized for each company separately, to the total number of their patents. The company Xerox was strong in the beginning of the 1990s. The main activities concerned basic principles and elements such as binary diffractive optical surface and beam shaping elements with prominent applications especially in image or document scanners.

The company Panasonic (including formerly Matshushita) shows, in general, a permanent steady patent activity with changing main application targets in optics for consumer electronic systems such as optical pickups (e.g., CD, DVD) or display technologies. Samsung mainly addressed optoelectronic systems for consumer products (e.g., pickups for data storage devices, mobile phone cameras, LED illumination systems, and display applications); however, their activities have started only a few years ago with a maximum in 2007/2008. The patent activities of Zeiss began with a moderate number of publications in the years before 2000 followed by an increase in the mid years of the last decade. Here, the dominant application field in using diffractive optical elements concerned beam shaping in the illumination systems of lithographic tools for semiconductor manufacturing industry (stepper/scanner). Further patents of Zeiss address imaging systems

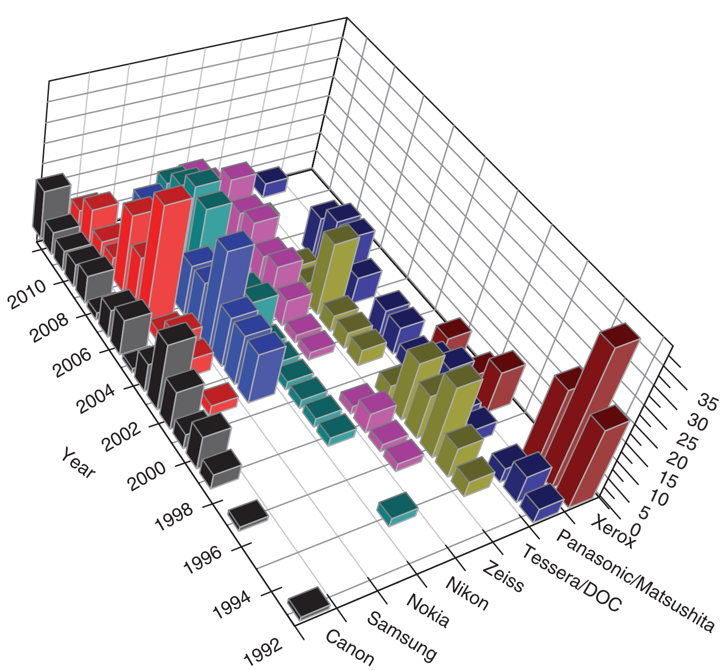

Figure 3 Temporal progress of the patent activities in the field of 'diffractive optics' for selected companies. The z-axis is normalized for each company separately to the total number of their patents.

with diffractive lenses such as microscope objective lenses or head-mounted displays. Patents of Digital Optics Corporation (DOC), which is now a wholly owned subsidiary of Tessera Technologies, can be traced back until the mid-1990s. In the 2000s, *DOC* patented significantly in exploiting DOEs for illuminations systems, especially, for applications in microlithography. Meanwhile, DOC/Tessera has a strong focus in optics for consumer products, e.g., camera modules and imaging systems for smartphones. Nokia was mainly active in the mid-2000s with a main focus in patenting DOE-related basic principles and applications for head-mounted displays. For the Japanese company Nikon, a considerable increase in patent activities in the mid-2000s concerning diffractive optics is observable. Essential application fields of Nikon are exposure systems for microlithography and, more recently, imaging systems such as microscope objective lens, eyepieces or photo lenses.

The development of the patent activities on diffractive optics of Canon deserves closer attention. Canon is a pioneer in using diffractive optical elements in combination with refractive lenses to form hybrid systems for imaging applications, and as already mentioned, Canon holds the largest number of published patents. In the beginning of the new millennium, Canon experienced major attention when they succeeded in reducing dramatically volume and weight, especially of telephoto lenses, by introducing DOEs.

The most decisive improvement concerned the aspect of efficiency achromatization of the DOE. Here, the diffraction efficiency of the DOE guarantees nearly 100% over a broad spectral bandwidth. The central element for efficiency achromatization consists of a selected multilayer relief configuration, which takes advantage of the dispersion characteristics and/or the introduction of additional structured interfaces within the diffractive structure. A typical schematic embodiment of this approach is shown in Figure 4 (top). Here, two single-layered DOE structures are arranged to face each other and are separated by an air gap of a few microns. The two single-layered DOEs are formed to have equal grating pitches but differ in grating heights and in material parameters. For broadband efficiency achromatization, the two materials with specific dispersion characteristics and adapted profile depths have to be chosen properly. In Figure 4 (bottom), the calculated diffraction efficiency η for a double-layer system made of an inorganic glass and a transparent resin is shown. The calculation is based on scalar approximation, where an optimum profile depth (d_1, d_2) is assumed for both surfaces.

Figure 5 shows the temporal development of the patent activities of Canon in the field of diffractive optics where three stages can be distinguished. The essential

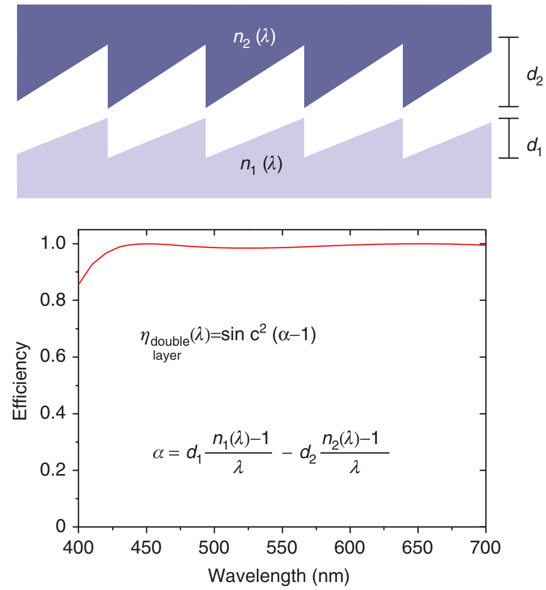

Figure 4 Concept of multilayer DOEs for efficiency achromatization. Top: two equal periodic diffractive structures with different step heights and realized in different media are facing each other. Bottom: calculated diffraction efficiencies for optimum profile depths following the scalar approximation of the displayed formula.

characteristics of each stage is visualized and highlighted by the underlying curve. The first stage, from the mid-1990s up to the year 2002 is characterized by a strong increase in published patents. At that time, also the first commercial telephoto lens systems based on the DOE concept (e.g., 'Canon EF 400mm f/4 DO IS USM' and 'Canon EF 70-300/4,5-5,6 DO IS USM') were introduced into the market and widely convinced the customers by keeping the promises in quality and compactness of the products. After that maximum, a decay in the number of published patents followed, and also the market activities seemed to have reduced. In this period, Canon was very cautious in presenting new products based on the DOE concept, and in discussion forums in the Internet, it was already stated that 'Diffractive Optics is dead!' (http://www.dpreview.com/forums/post/25226275).

Canon's recent activities oppose this assumption completely. A clear patent offensive with a strong increase in their patent activities on DOEs can be observed with the second largest number of published patents in 2012 (Figure 5 bottom). Analyzing the content of the relevant patents allows distinguishing roughly between two main targets. A first dominant aspect concerns the composition of the DOE with optimized efficiency over a broad spectral range, and the second aspect addresses a broad range of different telephoto lenses.

Figure 6 schematically shows the example of recently presented DOE concepts combining two DOE structures,

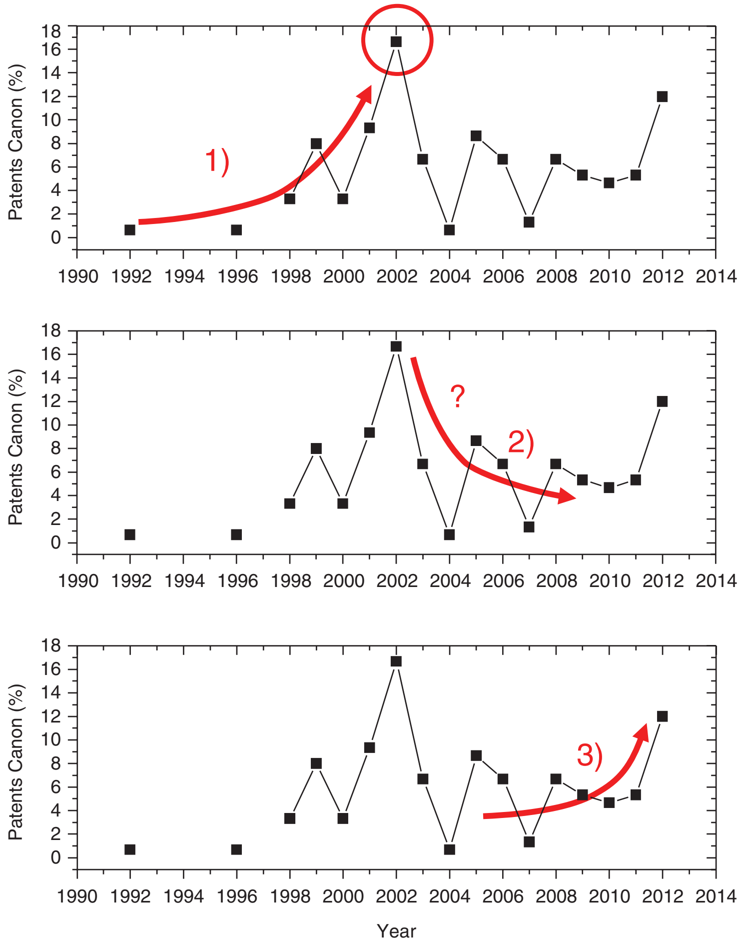

Figure 5 Temporal development of the patent activities of Canon in the field of diffractive optics separated into three stages. From the mid-1990s up to the year 2002, a strong increase in published patents is observable. After the maximum, a decay in the number of published patents followed. Currently, a clear patent offensive with a strong increase in their patent activities on DOEs can be observed.

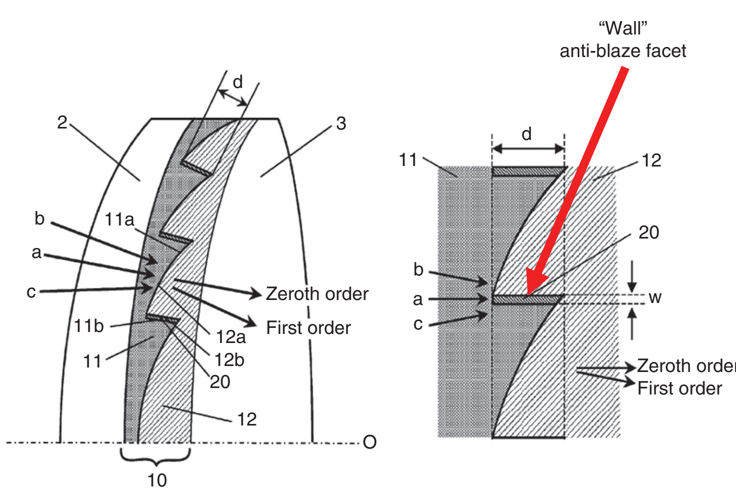

Figure 6 Schematic cross sections (left) of a combined diffractive-refractive element as presented in US patent US 2011/ 0304915 A1 [15]. Special emphasis is laid on the antiblaze facet – the 'wall' – (right), to reduce unnecessary light by introducing absorbing, reflective, or transitive layers of selected materials.

which are sandwiched between refractive surfaces. The depicted cross sections in Figure 6 (left: part of the combined hybrid element as an overview; right: detail of the contact area between both DOE surfaces) are transferred from US patent US 2011/ 0304915 A1 [15] (Figures 3 and 4). In comparison to former concepts, an essential detail of the new approach is the fact that an air gap between the adjacent DOE layers is dispensable. With the lacking air gap, the heights of both involved DOE profiles are identical, and therefore, the parameters for optimizing the chromatic efficiency behavior of the combined element are reduced. A further detail concerns the suggested material selection where, at least for one DOE profile, resins are proposed. In the relevant patents, it was also indicated that a modification of the resins by introducing nanoparticles into the polymer matrix allows an adjustment of refractive index and Abbe number of the material. That means that, due to the introduction of nanoparticles, the design parameters for efficiency achromatization have increased. For the proposed profile design and material combination, a grating height between 9 and 10 μm is sufficient, which is much less than the typical 15–30 μm depth required in the design of the preceding patents. The missing air gap may also lead potentially to a simplified manufacturing process. Here, the combined DOE can be fabricated by filling a basic diffractive structure with the resin. A time-consuming and sensitive alignment procedure to adjust distance, orientation, and lateral position is not necessary.

A number of patents target on the definition of the antiblaze facet, which was also indicated as the wall in these patents (exemplary, see Figure 6 right; arrow marked). Here, the main issue is to reduce unnecessary light by introducing absorbing, reflective, or transitive layers of selected materials on the antiblaze facet [16–19].

Beyond the considerable efforts, which were made to broaden the patent portfolio with respect to basic DO elements, Canon also intensively strengthened their intellectual properties for applications in camera or telephoto lenses. Table 1 shows a list of patented photo lenses based on the DOE concept. Examples 1–6 are from the Web site "http://www.canonrumors.com/tag/diffractive-optics/", example 7 is from "http://www.fredmiranda.com/forum/topic/1131117" and the 8th example was found on "http://thenewcamera.com/canon-patent-news-500mm-f4-do-500mm-f5-6-do-600mm-f4-do-800mm-f5-6-do". Most of the presented examples are telephoto or super-telephoto lenses with small f-numbers. In the patents, especially, it is mentioned that the DO concept allows to reduce volume and weight of the lens systems. With a view to the release date of the patents, an increased activity in the last 2 years becomes obvious.

Table 1 List of patented photo lenses based on the DOE concept. With the exception of two small focal length systems the presented examples are telephoto or super-telephoto lenses with small f-numbers. All listed patents are released in the last two years.

No.	Type of photo lens	Patent data:(Patent Publication No./Release date/Filing date)
1.	16-35 f/2.8 DO	2011-145518/ 28.7.2011/15.1.2010
2.	EF 28 f/1.8 DO	2009-198960/ 09.03.2009/25.02.2008
3.	200 f/2, 300 f/2.8, 400 f/2.8, 600 f/4	2012-2999/ 05.01.2012/16.06.2010
4.	70-300 f/4.5-5.6 DO IS, 14 f/2.8 DO 600 f/4 DO IS	2012-78397/ 19.04.2012/30.09.2010
5.	EF 400 f/4 DO IS II	2013-64858/ 11.04.2013/16.09.2011
6.	600 f/4 DO IS 400 f/2.8 DO IS	2012-88427/ 10.05.2012/18.10.2010
7.	400mm f/2.8 DO 600mm f/4 DO	2012-88427/ 10.05.2012/18.10.2010
8.	600mm f/5.6 DO 800mm f/5.6 DO	2012-123152/ 28.06.2012/08.12.2010
9.	500mm f/4 DO, 500mm f/5.6 DO, 600mm f/4 DO, 800mm f/5.6 DO	2013-92575/ 16.05.2013/24.10.2011

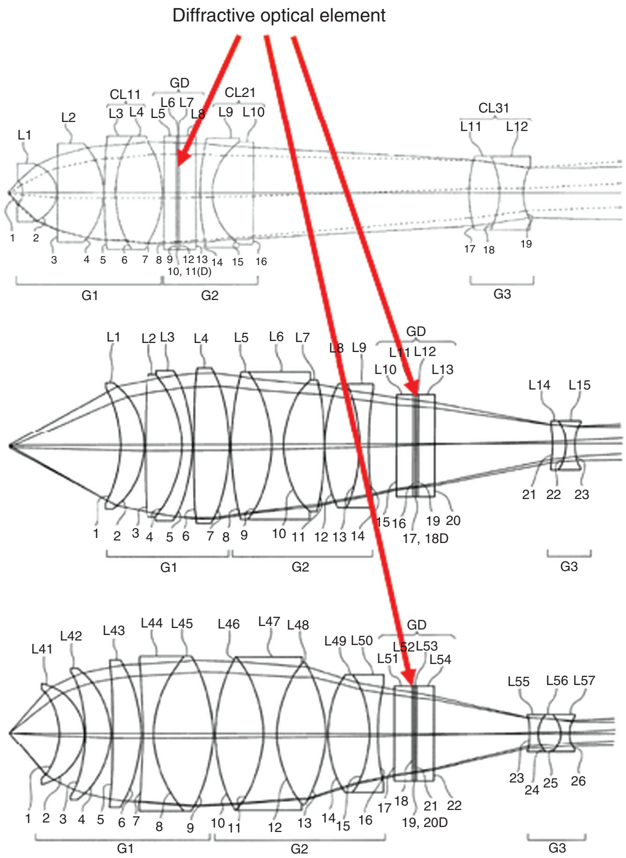

Figure 7 Three microscope objective lenses based on combining diffractive and refractive elements (top from US 2011/0102899A1 [21], middle and bottom from US 2010/0172034 [22]. The DOEs are marked with red arrows.

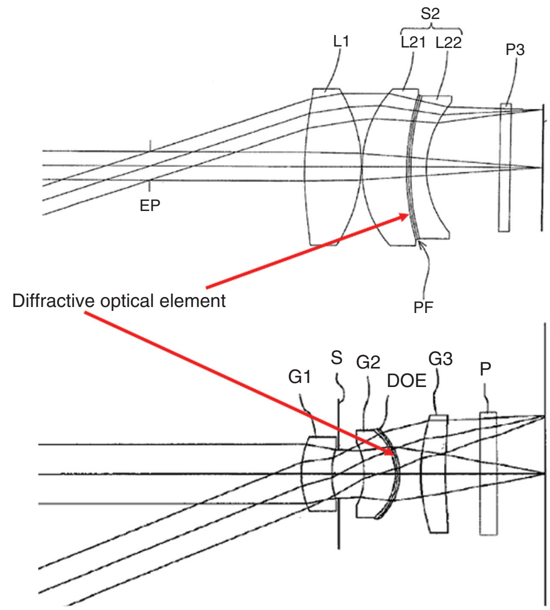

Figure 8 Lens drawings for small cameras based on the hybrid (diffractive-refractive) concept. Top from US 2010/0182697 A1 [23], bottom from US 2010/0007957 [24]. The position of the DOEs is marked with arrows.

DOEs applied for telephoto and super-telephoto lenses are not only published by Canon but also Nikon shows activities in this field (http://nikonrumors.com/2012/08/04/the-latest-nikon-lens-patents.aspx/). Nikon presented a 300 mm f/4 system [20] in which the introduction of DOEs results in a much shorter setup compared to a full dioptric system. Very recently, patents including DOEs as decisive elements were also presented for 18–300 mm and 28–300 mm zoom lenses (http://nikonrumors.com/2013/07/19/nikon-patents-a-camera-hand-grip-strap-and-two-zoom-lenses-with-diffractive-optical-do-element-inside.aspx/).

In addition to telephoto lenses, Nikon also files patent applications for further imaging optical systems. For example, Figure 7 shows three microscope objective lenses based on combining diffractive and refractive elements (upper example: Figure 1 from US 2011/0102899A1 [21], middle and bottom images both from US 2010/0172034 [22]) (Figures 1 and 5). The DOEs are marked with red arrows. The main targets, which are addressed by introducing the DOEs in the microscope objective lenses, are the correction of chromatic aberrations and minimizing aberrations at large angle of view. A third application field, which was addressed by Nikon to use DOEs in imaging systems, are small cameras for devices such as mobile phones, smart phones, or notebooks. As an example, Figure 8 shows lens drawings for small cameras based on the concept of combining DOEs and refractive elements (Figure 8 top from Figure 2 of US 2010/0182697 A1 [23], bottom from Figure 6 of US 2010/0007957 [24], position of DOEs marked with arrows). Also in this case, the DOE concept allows the optical system to be downsized and lightweight and still having an excellent optical performance.

4 Conclusion

The evolution of the patent landscape of diffractive optics shows a moving focus, which is wandering between the different applications for beam shaping and imaging. Especially, when regarding the recent patent activities of the Japanese companies Canon and Nikon, we found that DOE-based technology in imaging 'is not dead' as assumed earlier, but contrary, a very strong patent offensive of these companies becomes obvious. Hereby both aspects are addressed, on the one hand, basic concepts to improve the performance of the DOE and, on the other hand, the specific application in imaging systems such as photo lenses, microscope objectives, and small camera systems. From all these considerations, we expect a strong increasing number of real products based on DOEs in the near future.

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