

# Holography: 50<sup>th</sup> Anniversary of Dennis Gabor's Nobel Prize. Part II. An Engineering Perspective

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**Abstract:** The holographic principle, discovered by Gabor, and realized by Leith & Upatnieks and Denisyuk is discussed. The intrinsic value of this idea and its continuing ability to motivate and inspire engineers and applied physicists is reviewed. © 2021 The Author(s)

## 1. Introduction

Today across the globe holography is a very active area of research. There is simply no way to even briefly outline the breadth of research and engineering activity inspired by Gabor's wonderful invention [1-5]. Gabor would recognize the dilemma having himself been inspired by his fellow Nobel Laureates Lippmann, the Braggs, Raman (and many others), whose work his own complements. While Gabor foresaw some promising applications, no one could have anticipated how holography would develop and how it could be used to address so many technical problems. We can only wonder at what is yet to come.

## 2. Applications of Holography

Let us start with a brief discussion of the applications of holography and holograms:

Gabor wanted to view images more clearly, extracting more quantitative information by eliminating aberrations and greatly magnifying the results. Despite his own efforts and those of others at the time, the technique was not a practical success. I think therefore he would be extremely pleased to witness the explosive development of digital holography and its application for a range of wavelengths since the early 1990s. The use of his original in-line geometry, digital cameras and the development of a range of techniques, iterative and direct, to extract phase information from intensity measurements would be the perfect vindication of his approach. Every year new improved super-resolutions and improved depths of field are achieved, but holography always plays its critical role.

For most people holography is almost always first encountered as visual recordings, i.e. a three-dimensional image on a novelty sticker or a piece of art in a museum. These images, views through a virtual window, appear like magic requiring no scientific training to appreciate. Today, sharp, large-area, full true color images are widely available. One of a statue of Maxwell welcomes visitors to Maxwell's home in Edinburgh. Such static recordings immediately lead to two other wide spread applications: Data Storage, i.e. moving from storing analogue pictures to bits of data; and: Security, and the creation of easily visually authenticated labeling on currency, credit cards and tablets. Optically based verification, encryption and watermarking also build on these ideas. While static pictures are great, moving pictures are even better. Thus, the attempts to develop holographic projection systems, (*à la* Star Wars and Star Trek's *holodeck*), and the current developments of Virtual/Mixed/Augmented Reality Systems. Companies with prototype contact lenses systems providing such interfaces exist today.

What is interesting is that such systems (whether glasses or contact lenses based) require light to be managed (directed and channeled) within very confined spaces. Such dense, mass producible, low weight packaging requires the use of very thin optical elements for beam shaping. Whether these are diffractive elements (Lohmann's computer generated holograms), meta-surfaces or volume scatters, in all cases the holographic principle underpins their operation. Such passive holographic optical elements (HOEs) may be used to modulate the amplitude, phase or polarization of the field. HOEs for use with neutrons have been manufactured. HOEs can be applied to multiplex and de-multiplex signal, implement permutations and perform shuffling. The use of Spatial Light Modulators (SLMs), and MEMs have opened the door to programmable illumination in imaging systems, adaptive neural networks that learn and can be trained, optical computing systems and dynamic switching networks.

## 3. Modeling Holography

When explaining the holographic principle to our students we invariably describe the interference of two coherent fields, (object and simple reference), resulting in an intensity pattern. Thus, an off-axis transmission geometry is

commonly used. The recording of this intensity pattern, using a material with a linear response, results in a modulation of some material property (absorption or density). This permanently recorded material variation then acts to modulate any incident field, e.g. the simple reference beam, and it is described using a transmittance function. One of the resulting output terms, which using this recording geometry is usually angularly separated from the other terms, can then be clearly identified as containing all the necessary object field information. This is an incredibly accessible, very plausible, conceptually powerful and illustrative way of explaining the holographic principle. It builds naturally on plane expansions of fields and the concepts of spatial frequency and interference. During such an exposition even advance topics like Ewald diagrams and Wigner distribution functions can be introduced and used. Snell's law of refraction, the grating equation and Bragg's laws provide critically important context. For the engineer the central issue then becomes the determination of the light budget, i.e. how much light is scattered into the desired positions/angles.

Scalar transmittance function theory, (use of the Fourier transform to calculate the Fraunhofer far-field diffraction patterns) provides a good starting point when describing the modeling (calculation) of diffraction efficiency. The relationship with scatter in the Raman-Nath regime (occurring for acousto-optic modulators) and the associated coupled differential equations are of value. Usually introduction of the two-wave coupled wave equations, for a simple sinusoidal modulation, following Kogelnik, provides insights into multiple scatter by thick (multiply scattering) holographic gratings. Extensions to multicomponent gratings and multiple waves and eventually to full rigorous electromagnetic analysis (application of full boundary conditions and alternative computation approaches, e.g. finite elements), can be introduced naturally.

When designing diffractive optical elements, the rigorous electromagnetic models can be used to calculate a cost function permitting automatic searches for optimum grating parameter values. The resulting designs can then be fabricated as surface relief pattern. These models can also be used as part of algorithms solving inverse scatter problems allowing object information to be extracted from measured image data. We note that digital holographic imaging involved extracting phase information from intensity measurements. The resulting full field (amplitude and phase variation) at the camera is back-propagated through space, resulting in a series on image planes at different depths through the object.

All of the models, describing scatter of electromagnetic waves by a grating structure, presuppose that the modulated material parameters generated during recording/exposure, are well determined. The chemical composition, optimal use and modeling of photosensitive recording materials have itself received a great deal of attention. The stability, cost, sensitivity and spatial frequency response of such materials is of great practical importance. The non-local temporal and spatial responses of WORM, rewritable and polarization sensitive material, e.g. the anisotropic liquid crystal used in SLMS, are important areas of great potential commercial interest.

Clearly materials are a critical part of the support structure needed to permit the manufacture of products using HOEs. Fully understanding and characterizing materials, systems and optoelectronic devices, (light sources, SLMS, MEMs and digital cameras) provide links in the chain of modern technological development and commercialization.

#### **4. Conclusions**

We do not think we are alone in finding that holography (and indeed optics) continues to excite and to surprise. Pioneers like Gabor, Leith & Upatniek and Denysuk provide us all with opportunities and challenges far beyond what they themselves fully realized. Without their work the world would be a poorer place intellectually, commercially and technologically. Many of us would have missed having a great deal of fun.

#### **5. Acknowledgements**

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#### **6. References**

- [1] R. R. A. Syms, *Practical Volume Holography*, Clarendon Press, 1990.
- [2] H. Kogelnik, "Coupled wave theory for thick gratings," *Bell. Sys. Tech. J.*, 48, 2909–2945, 1969.
- [3] T. K. Gaylord, M. G. Moharam, "Planar dielectric grating diffraction theories," *Applied Physics B*, 28, 1-14, 1982.
- [4] R. K. Kostuk, *Holography: Principles and Applications*, CRC Press, 2021.
- [5] J. T. Sheridan, R. K. Kostuk, A. Fimia, *et al.*, Roadmap on Holography, *J. Opt. (IoP)*, 22 123002, 2020.