EMIL WOLF

EDITOR

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PREFACE

This volume presents five chapters, which deal with recent theoretical and experimental developments in modern optics.

The first chapter by Malin Premaratne discusses research on optical pulse propagation in biological materials. Specifically, it presents a review of recent advances in modeling of short optical pulses interacting with biological media at sufficiently low-power levels, which do not induce physical or chemical changes in the material.

The second chapter by Marco Bellini and Alessandro Zavatta presents a review of recent experimental developments regarding manipulation of optical fields by controlled addition and subtraction of single photons. The accurate engineering of the quantum state of light made possible by such operations has been used for generating novel, rather exotic nonclassical states and for testing fundamental laws of quantum physics. Applications of these techniques in the field of quantum information processing are likely to enhance the performances of existing protocols and lead to entirely new ones.

The third chapter by M. Kiffner, M. Macovei, J. Evers, and C. H. Keitel reviews researches on vacuum-induced processes in multilevel atoms. Based on the master equation, the underlying physical mechanisms are elucidated, both for single particles and also for collective atomic systems. Particular emphasis is placed on modifying or controlling the impact of vacuum-induced processes on the overall system dynamics, for example, by means of coherent laser fields. Numerous applications are discussed.

The fourth chapter by Guoqiang Li reviews recent advances that have been made in the field of adaptive lenses, varifocal lenses (Alvarez–Lohmann lenses), utilizing lateral shift between two conjugate components of cubic surfaces. It discusses the progress made in production of single-element adaptive lenses, including liquid crystal lenses. Refractive and diffractive lenses based on discrete electrodes, hole-patterned electrodes, modal control electrode, hybrid liquid-crystal alignment, polymer/LC materials are also described. Liquid lenses based on mechanical pressure, electrowetting effect, dielectric effect, and thermal effects are also discussed.

The concluding chapter by G. Gbur and T. Visser gives an overview of recent developments and applications, both theoretical and experimental, of light of different coherence properties. It includes accounts of researches on focusing and scattering of beams of any state of coherence, and it also discusses phase singularities of coherence functions and some applications.

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CONTENTS

CHAPTER 1

Optical Pulse Propagation in Biological Media: Theory and Numerical Methods

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Contents

1. INTRODUCTION

Science fiction captures the imagination of human mind and inspires us to make the dreams of today a reality tomorrow. Different versions

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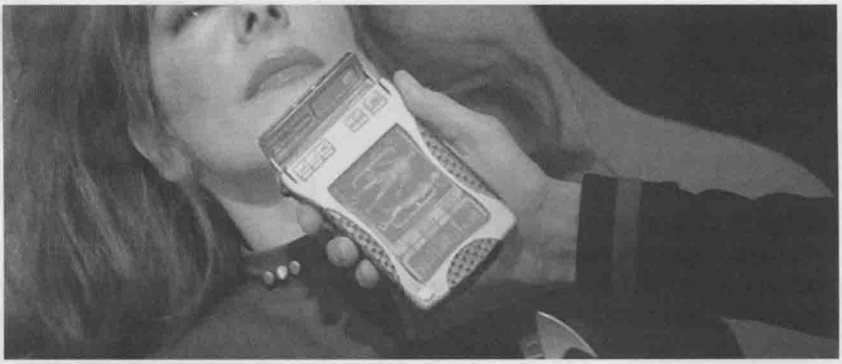

FIGURE 1 Usage of Starfleet Tricorder in Star-Trek series © Paramount Pictures and CBS Studios.

of the "Tricorder" device used in Star-Trek science fiction series can noninvasively scan any physical, chemical, or biological entity and cure ailments by hovering over their bodies (Figure 1). Recent advances in ultrasound and electromagnetics (including optics) could make "Tricorder" a reality. Increasingly, novel innovative ways of using light for clinical applications are developed by researchers all around the world (Wilson, Tuchin, & Tanev, 2005). For example, optical probes capable of carrying out tissue diagnosis offer significant advantages over standard biopsy and cytology techniques, in terms of both patient care and medical costs (Mourant et al., 1998). These probes have the capability to detect cancerous tissues because the interaction of light with tissue is strongly influenced by the composition and the cellular structure of tissue, which is obviously different for cancerous and healthy tissues (Wilson et al., 2005). Similarly, photodynamic therapy is increasingly used as a replacement or alternative way of treating cancerous cells with minimal side effects (Gobin et al., 2007; Prasad, 2003). Photodynamic therapy is the use of drugs (photosensitizers) that are activated by visible or near infrared light to produce specific biological effects in cells or tissues that can be exploited to achieve a particular clinical endpoint (Wilson et al., 2005). Recently, nanoshells have also been used as the activating medium (Gobin et al., 2007). When photosensitive dyes are used, cancerous cells are killed by injecting them in the vicinity of the cancerous cells and then transferring them to a toxic state using laser light (Niemz, 2004). In case of nanoshells, the heat generated by the nanoshells irradiated with resonant laser light causes the destruction of cancerous cells (Gobin et al., 2007). Laser-induced interstitial thermotherapy (LITT) is another technique used for tumor treatment, which makes use of the possibility of localized tissue coagulation (Niemz, 2004).

LITT was recently introduced to treat tumors in retina, brain, prostate, liver, and uterus (Niemz, 2004). Lasers are also being used for diagnostic and therapeutic purposes in ophthalmology, where the conventional incoherent light sources fail. For example, retinal glaucoma and retinal detachment can be accurately assessed and diagnosed by using confocal laser microscopy (Niemz, 2004).

All these developments relies on having a detailed understanding of light propagation through tissue. Such understanding can only be gained by creating sufficiently accurate models that can capture the essence of light interaction with biological media. Experiments are a vital part of this model-making process where they provide a solid basis and sound understanding necessary to conceptualize the fundamental ideas/axioms central to a model. Good models enable one to make predictions beyond their initial experimental base and discover novel phenomena. For engineers, these models eventually provide a way to optimize and fine tune techniques/devices that would have not been possible in other means. For example, heat is generated due to the interaction with light and tissue. The resulting local tissue temperature is of prime importance in laser surgery and depends, in turn, on the spatial distribution of the incident radiation. A detailed modeling is required to determine the duration of the laser light exposure of tissue for a successful surgical outcome. Errors cannot be tolerated in such clinical settings where the outcome might decide the fate of a patient undergoing laser surgery! Moreover, the development of diagnostic techniques such as optical coherence tomography, confocal microscopy, light scattering spectroscopy, and optical reflectance microscopy requires a fundamental understanding of how light scatters from normal and pathological structures within tissue (Wilson et al., 2005). In addition to these, lasers are used in ophthalmology, gynecology, urology, and many other fields (Huang et al., 1991; Niemz, 2004; Webb, 1996). Therefore, it is important to understand the effects of various optical parameters (i.e., model parameters) and their effect on the incident and scattered light to interpret these measurements appropriately (Mourant et al., 1998).

Increasingly, it has become clear that much can be learned about biological media by using temporal optical interactions. Most importantly, different cross-talk problems (i.e., interfering signals) arising in the steady-state optical interactions with biological media can be mitigated using properly executed temporal probing techniques (Tuchin, 2007; Welch & van Gemert, 1995). For example, short light pulses can be used to enhance image resolution in optical tomography techniques as cleverly exploited in the time-resolved spectroscopy area (Arridge, 1999). Another area of importance is optical coherence tomography (OCT), which uses low-coherence interferometry to produce a two-dimensional image of optical scattering from internal tissue microstructures in a way that is analogous to ultrasonic pulse-echo imaging (Huang et al., 1991). Both low-coherence light and ultrashort laser pulses can be used to map internal structures of biological systems. An optical signal that is transmitted through or reflected from a biological tissue will contain time-of-flight information, which in turn yields spatial information about tissue microstructure (Huang et al., 1991).

Given the many facets of recent advances in biology and optics, and the pace and overdrive of the innovation, it is a formidable or even an impossible task to map the current state of these technologies in a single snapshot. Many articles have comprehensively covered the trends and techniques in **static** optical fields interacting with biological media (Peraiah, 2002; Pomraning, 2005; Welch & van Gemert, 1995). Therefore, our primary aim is to cover the **transient** characteristics of optical fields propagating through biological media at sufficiently low power levels, which do not induce physical or chemical changes in the material. We specifically look at short, low-intensity pulses interacting with biological media and discard any light-induced permanent changes (e.g., tissue damage and ablation) or secondary emission processes (e.g., fluorescence and phosphorescence). This review is organized as follows: In the Section 2, we review the basic features of light scattering from biological media. We point out some specific features and provide pointers to literature for specific details. In Section 3, we look at the quantitative aspects of light propagation through tissue by discussing the general structure of the transient photon transport equation and related quantities. One major component of the photon transport equations is the scattering phase function, which takes care of the details of specific features of the scattering objects. We provide a catalog of many known phase functions and highlight their features, so reader can make an informed decision when selecting a phase function for analysis of biological media. We specifically point out the fact that further research needs to be done in coming up with better phase functions for biological media. Section 4 shows various ways of solving the transient photon transport equation and highlights the strengths and weakness of each method briefly. Most importantly, it is expected that this section provides enough pointers to literature where the reader can learn analogous variants of the methods covered in this section. Thereafter, we conclude this review in Section 5.

2. LIGHT SCATTERING

Scattering of light is a fundamental property of any heterogenous optical medium. Any medium other than a vacuum is heterogenous in some sense and hence scatter light (Bohren & Huffman, 1983). Light gets redirected or scattered when it encounters an electromagnetically active obstacle or inhomogeneity. Such redirection of energy can be used to learn about the scattering objects and thus enable one to do measurements and characterization of objects remotely/noninvasively. However, to gain a deeper understanding about how this can be achieved, it is vital to build an intuitive understanding of light interaction with material. Among the plethora of interactive mechanisms initiated due to such interactions, light scattering dominates. Having said that, it is important to understand that scattering does not always take place when photons interact with material (Born & Wolf, 1999). In certain instances, photons could get absorbed by the media and the energy in the photon may get dissipated as heat. In other instances, the absorbed light may get re-emitted after a time delay with a less energetic photon (Barron, 2004). This process is known as fluorescence. However, in certain fluorescence materials, multiple photons get absorbed and high-energetic photons get emitted. If the fluorescence takes places slowly for longer hours, the associated process is known as phosphorescence (Hercules, 1966).

If a photon gets absorbed by a certain media, then the energy of the absorbed photon must correspond to the energy required to make a discrete transition from a lower-energy level to higher- energy level in a material. In contrast, scattering of photons from a material could take place regardless of the structure of allowable energy transitions in the material. If the incident photon interacts with a characteristic energy level, there is a very good probability for the generation of photons with different energies compared with the incident photon energy. Interestingly, if the incident photon energy is close to an allowed energy transition in the scattering material and interacts with one of these characteristic energy levels, significant enhancement in the scattering strength can be observed. This type of enhanced scattering, usually called "resonance scattering," has characteristics significantly different to "normal scattering" (Kokhanovsky, 2001).

2.1. Classification of Scattering

If the scattered photon energy is exactly equal to the incident photon energy, then the scattering event is termed "elastic." Example of elastic scattering include Mie scattering and Rayleigh scattering observed in scattering from objects such as large dielectric objects (size is measured relative to wavelength of the incident radiation) and biological cells (Bohren & Huffman, 1983). Because biological media are made of many dissimilar constituents, their optical scattering properties including scattering strength provide a natural basis for their classification (Tuchin, 1997).

Strongly scattering (opaque) media examples include skin, brain tissue, vascular walls, blood, and sclera where multiple scattering dominates and

Weakly scattering (transparent) media examples include the cornea and lens in the anterior eye chamber where low-order, independent scattering events dominate.

However, it is to be noted that most of the biological media are anisotropic (i.e., have different properties in different directions), and hence it is important to account for scattering anisotropy especially in small-volume scattering studies. This has been somewhat successfully achieved by introducing scattering phase functions that describe the probability of scattering in a particular direction relative to incident radiation. Most widely used phase functions include Henyey–Greenstein phase function (Henyey & Greenstein, 1941), Gegenbauer kernel phase function (Yaroslavsky, Yaroslavsky, Goldbach, & Schwarzmaier, 1997), and Mie phase function (van de Hulst, 1981). In conjunction with these different variants of phase functions, empirical figure-of-merit (FoM) parameters known as similarity-rules have been widely used in tissue-optics community to concisely capture diffusive and anisotropic features in a cohesive platform (van de Hulst & Graaff, 1996). However, apart from their intuitive appeal, such classifications do not provide adequate quantitative assistance for analysis. Even though not that widely investigated yet, two other complexities of prime importance are the influence of medium on the coherence of light interacting with the medium and its state of polarization (Nieto-Vesperinas, 2006; Wolf, 2007).

2.2. Quantitative Modeling

A detailed quantitative understanding of how light propagates in tissue requires the incorporation of key relevant parameters needed for describing an optical signal in a medium, namely, wavelength, absorption, diffusion, anisotropy of scattering, coherence, and polarization. Such an understanding is paramount for the interpretation of diagnostic measurements to render meaningful results and for the development of therapeutic techniques. However, a simple relationship among the above fundamental parameters cannot be made because of the intricate dependency of the biological and optical properties of the biological medium on the local light intensity. For example, diagnostic methods that use fluorescence require a thorough understanding of targeted molecular energy absorption and emission rates at both exciting and emission wavelengths (Welch & van Gemert, 1995).

In addition, living biological media constantly change their properties due to intrinsic biochemical processes and external stimulations (Alberts et al., 1998; Saterbak, McIntire, & San, 2007). This time-dependency further complicates the mathematical description and subsequent numerical solution. In principle, Maxwell's equations can be integrated to calculate the optical response of a biological medium excited by an external/internal optical source. However, this can only be accomplished by having a detailed knowledge of tissue dielectric properties that is hard to acquire or even represent in current computing platforms (Barnes & Greenebaum, 2007; Foster & Schwan, 1989). Lack of this detailed knowledge of dielectric properties of tissue forces us to seek approximate methods that nonetheless provide sufficient information to describe almost all experimental results. One such method is photon transport theory that exploits the wide knowledge and experience of radiation transport in stellar atmosphere and propagation of neutrons in a nuclear reactors (Chandrasekhar, 1960; Pomraning, 2005; Rybicki & Lightman, 2004). Photon transport theory essentially ignores the wave features of propagating electromagnetic fields such as diffraction and interference but complies with other essential principles such as conservation of energy and momentum (Pomraning, 2005). Photon transport theory is based on the conservation of energy along an infinitesimal line segment in the scattering media and hence it could accurately predict light intensity distributions within biological media (Premaratne, Premaratne, & Lowery, 2005). However, as many authors have reported, it fails to account for observed coherent back-scattering peaks from dense scattering media including tissues (Yoo, Liu, & Alfano, 1990). Moreover, there is much controversy about how inhomogeneous media (i.e., those with varying refractive index, varying scattering parameters, and varying absorption properties) are to be handled in the photon transport framework (Bal, 2006; Premaratne et al., 2005). Without dwelling on this debate on the intricacies and on the precise format of photon transport equation, we can study different analytical and numerical strategies applicable under general conditions. Any variants from the standard techniques can be handled very easily because only trivial changes need to be made to underlying algorithms/concepts.

Even though monochromatic, steady-state photon transport in biological media found some applications in optical tomography and sensing areas, higher sensitivities or resolutions can be achieved by resorting to temporal and/or frequency domain methods (Leitgeb, Hitzenberger, & Fercher, 2003; Pal, Basu, Mitra, & Vo-Dinh, 2006; Yun, Tearney, de Boer, Iftimia, & Bouma, 2003). Especially, temporal waveforms (e.g., pulses) can be used to selectively excite certain types of molecules and to reduce the overall cross-talk due to different inhomogeneous features contributing significant amount of scattered light to the boundary where a detector is placed. When operated in steady state, there is no simple way to distinguish between these separate contributions from the main signal and cross-talk because such phenomena inevitably introduce measurement