Environmental and medical applications of photonic interactions

Svanberg, Sune

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Environmental and Medical Applications of Photonic Interactions

Sune Svanberg

Department of Physics, Lund Institute of Technology, and Lund Laser Centre, Lund University, P.O. Box 118, S-221 00 Lund, Sweden

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Abstract

Optical spectroscopy, and in particular laser spectroscopy, provides numerous possibilities for advanced diagnostics and multi-spectral imaging with real-time capability. We describe applications to the environmental and medical fields and it is noted that the basic approaches are very similar in both areas. Environmental diagnostics discussed includes satellite imagery, long-path absorption atmospheric spectroscopy, differential absorption lidar, gas correlation imaging and fluorescence lidar imaging of vegetation and historical building facades. The medical field is illustrated by photodynamic therapy, laser-induced fluorescence diagnostics, scattering spectroscopy and optical mammography, gas in scattering media absorption spectroscopy and imaging with laser-produced X-rays.

1. Introduction

Spectroscopy and multi-spectral imaging offer unique possibilities for observing the physical world. Because of the wavelength-specific interaction between electromagnetic radiation and matter it is possible to gain information of the chemical constituents of an investigated sample, and provide diagnostic information. Environmental and medical diagnostics are of special importance for mankind. However, the techniques employed here also frequently find their counterparts in the observation of the micro- as well as the macrocosmos, i.e., in elucidating the world under the microscope or scanning the depths of space in astronomy. In multispectral imaging, chemical or composition information is extracted from images recorded in different wavelength ranges, much adding to the information contents obtained in normal imaging, which mostly focuses on structural features retrieved by pattern recognition. Here the “on-board computer”, the brain, provides unprecedented multiplexing power, but for specialized tasks computers perform the task even better. However, the brain has limited multi-spectral capability, because of the limited spectral range, 400–700 nm accessible by the vision. Computer processing allows the identification of image elements fulfilling a specific criterion, e.g., of displaying cancer or forest decline. Any multispectral imaging must start with the pure spectroscopy of the individual constituents or image elements, where the spectroscopic finger-print is matched to conventional methods and wisdom in characterizing phenomena.

The emerging of lasers, advanced spectrometer concepts, CCD detectors and powerful computers has enabled a fast development of methods and technologies which are continuously being refined, but which in many cases have reached an operational/industrial level. A broad survey of spectroscopic techniques for basic studies and practical applications is provided, e.g., in Ref. [1]. Here numerous references to books, reviews and key papers to the many diverse facets of spectroscopy are provided exposing the numerous actors in the field around the globe. For limiting the scope, and for the convenience of the author, the present paper will mostly draw examples from work performed at the Lund Institute of Technology, Sweden.

We will focus on diagnostic applications in environmental and medical monitoring. Amazingly, the techniques are very similar in the two areas, which may seem to be very diverse. However, common to both is the remote and non-intrusive monitoring required and the need to perform the measurements under the normal atmospheric conditions in which the environment and our lives unfold. As we shall see, the differences largely are reduced to a matter of size of optical elements or energies in the light pulses employed.

Environmental monitoring is largely motivated from needs to assess the influence of pollutants and the control the efficacy of legislative actions. Global and long-term measurements related to greenhouse gases or ozone holes are important, but also regional and local studies of pollution are of great importance because of the impact on man and his environment. Environmental monitoring comprises the atmosphere, the hydrosphere as well as land, and for all aspects powerful spectroscopic techniques can be applied. Satellite imagery mostly operate in the reflective mode, where the modification of the sun radiation by the surface (land or water) is studied. Absorption features in the background radiation passing through atmospheric layers can also be used for air pollution monitoring. An interesting variety which is particularly suitable for imaging is gas correlation spectroscopy, where the radiation from the scene under investigation is filtered through a cell containing the gas under study. We will also discuss active remote sensing techniques where an artificial illumination source is employed. Differential optical absorption spectroscopy (DOAS), tunable diode laser absorption spectroscopy (TDLAS) as well as differential absorption lidar (DIAL) technique are examples of such methods for atmospheric monitoring. Laser-induced fluorescence (LIF) is a powerful active technique for studies of water as well as green vegetation and even facades of historical buildings. Several examples illustrating these possibilities will be given.

Medical diagnostics can be performed with a multitude of systems with imaging capability: X-ray radiography, magnetic resonance imaging (MRI), ultrasound, single photon emission computerized tomography (SPECT) and positron emission tomography (PET) are the most important methods. Optical investigations can supply additional information. Imaging in reflectance is basically what the trained doctor’s eye is performing. By multispectral imagery
the colour contents can be more accurately monitored and measurements outside the visible region are also possible. Thus, thermovision systems can under certain conditions reveal superficial tumours. Transillumination with temporal resolution can remedy the heavy multiple scattering occurring in tissue and can allow, e.g., optical mammography. Techniques for the assessment of the concentration of absorbing species inside highly scattering media have also been developed, including measurements of dispersed free gas using the gas in scattering media absorption technique (GASMAS). On a small depth range, multi-photon fluorescence microscopy (MPFM) and optical coherence toography (OCT) can be performed to image structures down to the cell level. Finally, laser-induced fluorescence or Raman spectroscopy have proven very useful for early detection of malignant tumours and atherosclerotic transformation of blood vessels.

Laser radiation can also be used for therapeutic applications. The most common one is for thermal coagulation or cutting of tissue. Photodynamic therapy ( PDT) is a non-thermal modality where malignant cells, after selective uptake of a sensitizing drug, are brought into necrosis by red laser light irradiation, mediating the release of singlet oxygen.

The development of compact terawatt lasers have also enabled extremely short and intense X-ray pulses to be generated with possible medical application. In the following we will give illustrations from most of these different fields.

As has been mentioned above there are many parallels between environmental and medical diagnostic techniques. Below some of these are indicated, where the concepts are the same but the spatial dimensions and the amount of light used differ vastly.

### Phenomenon utilized

<table>
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<th>Medical variety</th>
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## 2. Environmental monitoring using photonic interaction

### 2.1. Satellite imagery

Most satellites for environmental monitoring have polar orbits about 1000 km above the surface of the earth. Modern satellites mostly operate in a push-broom multi-spectral mode, where a line on the ground is imaged along the slit of a spectrometer which disperses the reflected radiation perpendicularly to the slit. The dispersed light falls on a ccd detector where the columns in the matrix correspond to different spatial locations and the rows display the spectrum in these different locations. The spatial resolution typically ranges from 1 km down to few metres. Prominent features in spectra are absorptive imprints due to chlorophyll and other pigments through the visible range, and due to water in the near-IR region allowing earth resource inventory. In the infrared region around 10 μm the surface temperature, mostly of the oceans, can be mapped. Radar satellites operate in the synthetic aperture mode (SAR) to keep up the ground spatial resolution in spite of the drastic decrease in the antenna diameter over wavelength ratio when going from the visible to the microwave region. These satellite employ active transmission of radiation and have all-weather capability since they image through the clouds. High-resolution satellite sensors can also look for sharp spectral features in backscattered solar radiation, or in limb absorption geometry using the sun-disc or bright stars as the light source. In this way the distribution of atmospheric molecular pollutants can be mapped. E.g., the ozone layer is constantly being monitored in this way. The powerful techniques of satellite imagery are covered, e.g., in [2,3].

Frequently, environmental parameters need to be monitored on a local scale and then a plethora of powerful techniques are available. We will now illustrate air pollution monitoring using fixed or mobile installations.

### 2.2. Long-path absorption measurements

Gas analysis can be performed by measurement of the absorption over a given distance and relating the specific absorption to the average gas concentration using the Beer–Lambertian law. These line-of-sight measurements can use broadband artificial light sources in combination with a high-resolution spectrometer, or tuneable lasers. The DOAS technique is widely used for line-of-sight measurements of urban pollution levels (see, e.g., [4,5]). A high-pressure xenon lamp is used as a light source and a flying-slit spectrometer or ccd spectral read-out is employed. NO$_2$, SO$_2$ and O$_3$ are normally measured, but also NO and polyaromatic hydrocarbons (benzene, toluene, xylene . . . ) can be monitored. Commercial equipment is widely available.

Tuneable semiconductor lasers provide new possibilities for atmospheric absorption measurements. Direct laser action was recently extended down into the violet region using GaN-based structures, whereas AlGaAs structures, vertical-cavity surface-emitting lasers (VCSELs), and quantum-cascade lasers provide access through the visible, near-IR and IR regions. Wavelength- and frequency modulations schemes allow extremely low absorptions to be picked up. The UV and near-IR regions can be reached by sum- or difference generation schemes (See, e.g., [6,7]). Figure 1 shows a set up for reaching the 254 nm line of atomic mercury, and cell spectra for low and atmospheric pressure show the separated isotopic lines and the pressure-broadened composite line. By carefully selecting the individual emission regions it is possible to cover three gases simultaneously, e.g., by using sum-frequency mixing of 438 nm (NO$_2$) and 975 nm (H$_2$O) to 300 nm (SO$_2$) [8], or difference-frequency generation from 760 nm (O$_2$) and 980 nm (H$_2$O) to 3.4 μm (CH$_4$) [7].
2.3. Differential absorption LIDAR

While it is not possible to determine where along the measurement line the absorbing molecules are located, a differential absorption lidar (DIAL) system allows just that (See, e.g., [9,10]). Here pulses of tuneable radiation are transmitted into the atmosphere and photons, which are elastically backscattered from aerosol particles or molecules (Mie and Rayleigh scattering, respectively) are collected by an optical telescope and detected temporally resolved. A schematic diagram of the Lund mobile lidar system is shown in Fig. 2 [11]. Typically, the laser source is switching from a wavelength where the pollutant of interest is absorbing to a neighboring non-absorbed wavelength every second shot and the on- and off-resonance lidar transients are accumulated in separate memories. The two curves are quite similar in terms of the backscattering features from particle clouds etc. but the on-resonance curve in addition shows the accumulated absorption by the studied gas. By dividing the two signals by each other for each range interval the effects of scattering inhomogeneities are cancelled and the ratio curve departs from the unity level to successively lower values. From the slope the range-resolved concentrations along the line can be evaluated and displayed. By scanning the beam through, e.g., a dispersing industrial plume its integrated concentration value can be determined as illustrated in Fig. 3. Here atomic mercury flowing from a chlor-alkali electrochemical plant is shown [12]. By multiplying the area-integrated concentration \([g/m^2 \times m^2]\) by the perpendicular wind velocity \([m/s]\) the total flux \([g/s]\) is obtained [13].

Certain pollutants occur in complex and spectrally overlapping mixtures. This is particularly true for the hydrocarbons, which have absorptive imprints due to the C–H stretch vibrational mode in the 3.4\(\mu\)m region. It is then necessary to be able to transmit a number of well-positioned wavelengths in order to separate the different gases. Then a fully tuneable optical parametric oscillator lidar transmitter is very useful. An IR lidar backscattering curve is shown in Fig. 4(a) [11]. Simultaneous monitoring of a cloud containing methane, ethane and propane is illustrated by raw intensity-divided curves recorded at selected wavelength pairs displaying species-specific differential absorption (curves (b), (c) and (d)). Curve (e) shows a case where both wavelengths are non-absorbed and the constant ratio level is displayed at all ranges. Note that the methane curve (b) exhibits a persistent slope due to the ambient presence of this gas, with the enhancement due to the cloud at 60 m distance. The ethane and propane curves only show a distinct step down at that distance.

Apart from industrial lidar monitoring we have extensively monitored pollutant gases of geophysical origin, i.e., from volcanoes, geothermal fields and mines [14]. As an example the SO\(_2\) plume for the Sicilian volcano Mt. Etna is shown in Fig. 5 [15,11]. Here the vertically firing lidar system was placed of the aft deck of an oceanographical research vessel making traverses under the volcanic plume flowing put over the Straight of Messina. It can be noted that a typical flux of about 50 tons/hour was recorded for non-eruptive background conditions. Lidar data were compared to DOAS recordings of the gas absorptive imprint in the down-welling radiation from the blue sky or in the light from the sun disc, tracked during the plume traverse. Recordings using the dispersive correlation technique COSPEC, extensively employed for routine volcanic monitoring were also recorded. By comparing all four measurement techniques the influence of diffuse atmospheric scattering on the measurement accuracy could be studied [15].

Atmospheric lidar techniques also include the utilization of Doppler shifts due to wind which can be detected by heterodyne techniques. Airborne lidar systems have been used for studies of aerosols and ozone and the lidar technique has also been demonstrated in Space Shuttle experiments.

2.4. Gas correlation imaging

Gas monitoring using ambient radiation as mentioned above can also be performed in the IR spectral region using thermal radiation [16]. The gas correlation principle, as introduced in Fig. 6, is particularly suited for imaging [17]. The underlying principle can be stated as “nobody knows a molecular absorption spectrum better than the gas itself”. Here, the scene is simultaneously imaged directly and through a cell containing an optically thick amount of the gas, the presence of which in the environment is under study. If certain areas of the scene contain the absorptive imprint of a multitude of specific rotational-vibrational lines this will influence the intensity of pixels in the directly recorded image, but can by definition not do so, since a maximum imprint is already present in the whole gas-filtered image (“nothing can become more black than black”). By dividing the direct image by the filtered one pixel by pixel, a differential image emerges where only areas of gas deviate from an otherwise constant ratio value. An example of an image from an ethylene emitting flare at
a petrochemical plant is shown in Fig. 7 [18]. Operationally, the processed and thresholded gas image is superimposed on a normal colour image and the flow of gas can be recorded in real time at video rate. The technique is particularly suitable for leak detection and remedy in the petrochemical and gas industry allowing explosion safety, environmental impact and pure economical advantages.

Fig. 3. Vertical DIAL scan of the atomic mercury plume emitted from an electrochemical plant. The measurements were performed at the mercury strong resonance line close to 254 nm. Total recording time was about 5 minutes. Data indicate a yearly emission of mercury of the order of 40 kg (From [12]).

Fig. 4. Differential lidar recordings of hydrocarbons around 3.4 μm. The radiation was generated by difference-frequency generation between a 1.55 μm idler beam from the OPO and a separate Nd:YAG injection-seeded laser operating at 1.064 μm. An illustration of a lidar recording is shown in (a). Differential absorption curves are shown for methane (b), ethane (c) and propane (d), and for the case when both transmitted wavelengths are off-resonance (From [11]).
2.5. Fluorescence LIDAR imaging

Surface characterization using passive optical imaging or radar scattering was illustrated for the case of satellite imagery in Section 2.1. Sometimes fluorescence can yield valuable additional information. It is then possible to use the fluorescence LIDAR technique, which has been applied to marine oil spill and algal bloom detection, to vegetation status assessment and for the monitoring of the facades of historical buildings (See, e.g., [9,19,20]). A frequency tripled Nd:YAG laser operating at 355 nm is a convenient excitation source, although multiple wavelength fluorescence induction can yield additional discrimination power.

We will illustrate the fluorescence lidar technique by two examples from historical monuments. The Lund mobile lidar system as illustrated in Fig. 2 was employed. An illumination spot typically 5 cm in diameter was scanned in a whisk-broom pattern across the surface, which was typically 50–100 m away, and induced fluorescence was collected by the lidar telescope and dispersed and recorded in an optical multichannel analyser system. By time-gating the detection to the arrival of the brief fluorescence burst, it is possible to discriminate background solar radiation and to operate in full sunlight.

Figure 8 shows data for an 8 × 8 m² area around a gate of the Lund Cathedral [21]. Fluorescence signatures are different for different stone types and show particularly strong imprints due to the invasion of biodeteriogens such as algae and lichen, and due to chemical agents applied for surface stabilization. Images recorded at a single detection wavelength are subject to geometrical artefacts, which, however, are eliminated by ratioing information recorded at two wavelengths, along the same principles as adopted in atmospheric DIAL measurements (Section 2.2). Different stone characteristics emerge. Generally speaking, spectral shapes rather than intensities are useful for substance identification, and here multivariate data analysis, e.g., principal component assessment, is particularly powerful.

Figure 9 illustrates data from the Parma Cathedral and Baptistery, showing algal and conservation treatment monitoring [22].

3. Medical applications using photonic interaction

3.1. Photodynamic therapy

We will start our discussion of medical applications with a description of photodynamic therapy (PDT), which provides a method to selectively eradicate malignant cells while leaving the normal cells intact. Here a particular chemical agent, a sensitizer, is administered to the body and localizes selectively to malignant cells. Using light matching an electronic transition of the agent, it is excited. The excitation energy is transferred to oxygen molecules, which normally are in their ground triplet state. The resulting singlet oxygen is very toxic to tissue and induces necrosis. There is a certain parallel to photosynthesis in the environmental field. There the combination of a particular chemical agent, chlorophyll, and light brings about the build up of organic material out of carbon dioxide and water in a cold photochemical procedure. PDT is from a certain aspect the opposite process; the agent in combination with light instead break down organic material into its components, also in a cold process.
PDT was first introduced at the turn of the last century. However, with the development of pure and efficient sensitizers combined with laser sources at the relevant wavelengths, the field has expanded a lot, first through the work of T. Dougherty, demonstrating the treatment efficacy of haematoporphyrin derivative (Photofrin), absorbing at 630 nm. Actually, the sensitizer absorption must fall within the range 600 nm to 1.4 μm to allow penetration into tissue. In practice it must also be below 1 μm in order to ensure enough energy to allow the energy transfer to oxygen. While most sensitizers such as mesotetrahydroxyphenylchlorine (Foscan; 652 nm), benzoporphyrin (Verteporfin; 690 nm) and lutetium texaphyrin (Lutrin; 732 nm) must be administered intravenously, the protoporphyrin IX (PpIX) precursor, C14-amino levulinic acid (ALA) has the advantage of additional possibilities of topical or oral administering. ALA is a natural constituent in the body, utilized as the starting material in the haem cycle. Strongly fluorescing and photodynamically active PpIX is produced at higher concentrations in skin tumours after applying an ALA-containing cream over the tumour a few hours before irradiation with light at 635 nm. The very efficient ALA-PDT was introduced by Z. Malik and J. C. Kennedy and has been used widely also in our group [23–25].

An example of an ALA-PDT treatment is shown in Fig. 10, where a squamous cell carcinoma is shown to be efficiently treated. A diode laser operation at 635 nm and at an output power of 1–2 watt is used for surface radiation for achieving a dose of typically 60 J/cm². PpIX is cleared from the body in a few hours and does not pose skin photosensitization problems which are typical for other sensitizers which require patients to be kept at low light levels for a few weeks.
Even at the most favourable wavelengths the penetration of light in tissue is limited to about 5 mm. In order to treat thick tumours and/or deep-lying tumours, fibre-based interstitial PDT is being developed. Light is then distributed into the tumour mass through a number of inserted optical fibres. A photograph of such a system is shown in Fig. 11 [26], where light from a high-power diode laser is split into six fibres inserted in a tissue phantom. A scheme of a more efficient system with six individually controlled treatment lasers is seen in Fig. 12 [27]. By turning a cylindrical light distributor disc by 30° with respect to the treatment position, light from three different diagnostic light sources can instead be injected into any one of the six treatment fibres and spectroscopic signals be picked up through the other five fibres to be analysed in a common spectrometer. In this way the distribution of the treatment light can experimentally be measured and controlled, and the oxygenation of the tissue can be monitored.

Fig. 11. Photograph of a six fibre system for interstitial PDT. Each fibre in this particular system can be used for transmitting therapeutic light and for measurements of the light flux through the tissue from the other fibres (From [26]).

Fig. 12. Scheme of new interstitial PDT system under development. On the top the six patient fibres are seen connected to individual diode lasers providing the therapeutic radiation. Below, the system is shown in a diagnostic mode, when the light distributor disc has been rotated by 30 degrees (for clarity the fibres not in action are suppressed in both figures). A diode laser operating at the same wavelength as the treatment laser can be successively switched into the six fibres, and for each position the diffuse light picked up by the other fibres can be measured. Alternatively, a white light source can be switched in and the haemoglobin absorption sensitive to the oxygen contents can be monitored. Sensitizer levels at each fibre position can also be assessed by laser-induced fluorescence employing a blue diode laser as the excitation source selected by the second selector disc (From [27]).

Fig. 13. Fibre-optic fluorosensor, based on a violet diode laser and a compact integrated spectrometer with array-detector read out (From [30]).

Fig. 14. Example of fluorescence imaging of a basal cell carcinoma. Contrast enhancement and immunity to geometrical effects are obtained by dividing the free-standing sensitizer-related peak at 635 nm with the blue autofluorescence intensity (From [34]).
can likewise be assessed by observing the blood absorptive imprint on transmitted white light. Likewise, the concentration of the sensitizer can be monitored by observing its specific LIF signal, as further discussed in the next section.

3.2. Fluorescence diagnostics

In the same way as LIF can provide environmental information, the fluorescence signature of tissue can be used for medical diagnostics. As we have already mentioned, sensitizing agents frequently exhibit a strong and characteristic fluorescence signal that can be utilized for localizing and demarcating tumours. Porphyrisns are best excited at the peak of their Soret band around 400 nm. If a shorter excitation wavelength is used (optimally around 340 nm), autofluorescence from endogenous chromophores can be used for tumour diagnostics, since the signatures do frequently differ from normal tissue. Fibre-optic fluorescence sensors with a compact pulsed nitrogen laser emitting at 337 nm have been much utilized. The laser light is transmitted to the tissue through the fibre, which also picks up and conducts the fluorescence signal to the entrance slit of a gated and intensified detector, displaying the full LIF spectrum for each laser shot. Instrument constructed in this way are described, e.g., in [28,29].

A simplified variety is shown in Fig. 13, where a violet diode laser at 397 nm is used to induce fluorescence which is recorded by a compact integrated spectrometer with array detector read out [30]. Since it combines efficiency with low cost it has been introduced in several developing countries [31].

Most medical diagnostic devices provide image information. It is also possible to build multi-spectral fluorescence imaging systems. Then a larger tissue area is illuminated and the fluorescence is simultaneously recorded in several fluorescence bands using special beam-splitting optics [32,33]. An example is shown in Fig. 14, where a basal cell carcinoma located under the ear of a patient is shown [34]. The spectral signatures of tumour and normal tissue are shown. Tumour tissue is characterized by a strong intensity increase at 635 nm due to the sensitizer, at the same time as the tissue autofluorescence level around 470 nm is reduced. Three detection bands utilized in this case are shown. By subtracting signals recorded at 635 nm by the signal at about 600 nm a background-free peak intensity is obtained, and this intensity is then divided by the blue intensity, resulting in a dimensionless quantity featuring enhanced contrast and immunity to detection geometry etc.

Fluorescence imaging can also be performed using a push-broom sensor, where multi-spectral imaging is performed line-wise in a similar way as in a satellite imaging spectrometer (Section 2.1). Instead of using the platform movement for the line advancement, it is achieved by tilting a scanning mirror. This technique employing the strong mercury line at 365 nm for excitation has been applied to gynecology [35]. By ALA instillation in the bladder, it is possible to detect dysplasia and carcinoma in situ using plain visual inspection, as performed in a commercial system by Stortz.

3.3. Scattering spectroscopy and optical mammography

By studying the propagation of light through tissue it is possible to gain information about the absorbing chromophores in the tissue and the scattering of tissue structures and in that way perform tissue diagnostics. This requires a good knowledge of tissue optics, since absorption and scattering are strongly intertwined in any measurements. It is possible to “orthogonalize” absorption and scattering by solving the light transport equations or by performing Monte Carlo simulations. A special challenge is to be able to achieve optical mammography by transillumination of the breast with light in the red and near-IR region [36]. Here it is possible to employ a pulsed near IR radiation source in transillumination and to electronically gate on the “early”, little scattered photons to attain geometrical contrast for visualization of possible tumours [37,38]. An alternative is to use a modulated light source and to observe the phase shift and contrast loss in the photon density waves emerging from the scattering tissue. The information contents is the same as in the time-resolved measurements, but the equipment may be simplified. There is a problem in that there are basically extremely few ballistic, non-scattered photons for a tissue thickness of 5 cm. Thus a high geometrical resolution is not possible. Tumour detection will then instead rely on whether there is enough contrast between the optical properties of malignant and normal tissue. Here the possible use of optical contrast agents is of particular interest. Much efforts have been invested in providing a tomographical back projection of the three-dimensional structure of the tissue from multiple measurements of the diffusive light. The future of optical mammography is still not obvious.

By studying the propagation of white light through tissue it is possible to obtain a true concentration determination of chromophores in the presence of scattering. Here femtosecond pulses can be focused into water or a photonic-bandgap fiber to generate white light. After passage of this light through the sample, spectral and temporal resolution of the photons is gained by crossing a spectrometer with a streak camera before the detection [39]. In this way the selective uptake of sensitizer can be studied in a more well-defined way than in measurements of fluorescence, which are influenced by quenching of the fluorescence light. Other scattering media, such as plant leaves can also be studied [40]. The technique also allows the measurement of the active substances in pharmaceutical preparations, which typically have a very strongly scattering matrix [41].

Overviews of laser-based medical diagnostics can be found, e.g., in [42–45].

3.4. Gas in scattering media absorption spectroscopy (GASMAS)

The spectral features of solids and liquids are broad and seldom sharper than 10 nm due to the interactions between the participating atoms. Thus the spectroscopic equipment used for the study of such samples seldom have a very high resolution. However, an many samples there are structures which are 10,000 times sharper—enclosures of free gas. Enclosures mean that the materials are then also scattering due to the changes in refraction index. Thus there is no straight-forward Beer–Lambertian law to analyse the results. Instead, the techniques wellknown in tissue optics (Section 3.3) can be used. We have recently combined the techniques discussed in Sections 2.2, 2.3 and 3.3 and
introduced a new spectroscopic method of considerable potential, the gas in scattering media absorption spectroscopy (GASMAS) [46,47]. Here the light from a single mode diode laser is conducted by a fibre to the sample, which is placed in proximity to the photocathode of a photomultiplier tube to allow a maximum detectivity of the diffusely transmitted light, which might be very faint. By wavelength- or frequency modulation techniques it is possible to sensitively detect the sharp absorptive imprint due to the gas. A set-up is shown in Fig. 15(a). Our first measurements have concerned normal atmospheric oxygen molecules, which were studied in matrices as diverse as polystyrene foam, wood, and fruits. Concentration assessment can be achieved by also performing time-resolved measurements with a pulsed laser at the same wavelength using a set-up very similar to an optical mammograph (Fig. 15(b)). Then the time-dispersion curve will give information on the “history” of different photons travelling short or long distances through the sample, as illustrated in Fig. 16. Here an experimental curve for a 4-cm thick slab of oxygen-containing polystyrene foam is shown, indicating that some photons actually travel 4 metres before reaching the detector! The successively stronger absorptive imprint in light that has travelled long distances is schematically indicated, and the mean travel time is evaluated to be used for concentration evaluation.

A particularly interesting application is to study gas diffusion through porous material. Then the sample is first stored in a nitrogen atmosphere for few hours, e.g., by placing it in a plastic bag which is briefly flushed from a nitrogen tank and sealed with a tape. After several hours the sample is taken out and placed in the GASMAS apparatus, and the successive reinvasion of the normal air into the sample can be followed by the oxygen signal as shown in Fig. 17 [48]. Here 10 mm thick samples of Norwegian Spruce and Balsa wood were studied and contrary to what could have been expected the Balsa wood exhibits a much longer time constant, probably related to well sealed individual cell compartments in the otherwise loose structure. Clearly, diffusion can be characterized by several time constants. The influence of surface coatings such as paints or plastic films can be readily studied. Internal pressure in a sample can also be monitored non-intrusively through the pressure-broadening of the absorption lines [46].

The monitoring of concentration ratios of two gases absorbing at close-lying lines eliminates the need for a detailed understanding of the photon transport through the sample and could give new insights in field as diverse as plant physiology and catalyst research.

3.5. Laser-produced X-rays

Medical application of X-rays has developed during 100 years and now constitute one of the most important diagnostic modalities. X-ray generation is accomplished through acceleration of electrons into a material with a high nuclear charge Z. With the development of short-pulse lasers with output powers in the terawatt range it has become possible to generate hard X-rays by focussing the radiation to a small spot on the surface of a high Z-material like tantalum. While this generation scheme is obviously more complicated and costly it can present some advantages which are mostly related to the small source size and the potential to reduce the X-ray dose by viewing techniques in an analogue way as discussed for optical mammography in Section 3.3. Early high-resolution imaging was reported in [49,50]. While it is easy to understand why scattered photons need to be eliminated in the optical regime due to the obvious and massive light scattering it is not so evident for X-rays which are known to produce sharp images of ribs etc. However, in whole-body X-ray radiography without any special precautions actually 90% of the photons reaching the plate are Compton scattered and contribute only do a diffuse background. This background is frequently reduced using anti-scattering (straight-vision) grid plates between the
patient and the plate to reduce the photons having the wrong angle. The price is obviously that the patient has to be exposed to a higher dose of ionizing radiation. The potential of medical X-ray gated viewing was first pointed out in [51]. We have performed detailed studies of gated X-ray detection using a 10 Hz high-energy laser system in combination with an X-ray streak camera [52], and also demonstrated gated tomographic X-ray imaging [53].

Contrast agents are frequently used in radiography. An image of a rat featuring an iodine contrast agent being excreted and accumulated in the urine of the bladder is shown in Fig. 18 [54]. By utilizing the sharp K emission lines from the laser-produced plasma and employing two different target materials so that the K-lines bridge the K absorption line of the contrast agent (at 33 keV for iodine, at 50 keV for gadolinium, which both are approved contrast agents), and by dividing two images taken with different target materials only the contrast agent survives the division, in a similar way as discussed above for DIAL or gas correlation remote sensing, and demonstrations are presented in [55]. Image recording with an ultra-short

![Time “history” of injected photons](image1)

Fig. 16. Experimental recording of the time-dispersion curve for photons traversing a 4 cm thick slab of polystyrene foam. The successively increasing relative absorptive imprint of the uniformly distributed gas is schematically indicated, as is the expression for the effective absorption in the sample. (From [47]).

![Oxygen diffusion curves](image2)

Fig. 17. Oxygen diffusion curves for two 10 mm thick slabs of Norwegian Spruce (short time constant) and Balsa wood (long time constant). (From [48]).

![Rat with contrast agent](image3)

Fig. 18. X-ray image of a Wistar Furth rat with a Gd-containing contrast agent being excreted through the urine in the bladder shown more opaque. The image was recorded with laser-produced X-rays from a rotating tantalum target being irradiated by a terawatt laser system (From [54]).

![Single-pulse image](image4)

Fig. 19. Single-pulse image of an extracted human ear bone, the Incus, recorded on an image plate with an exposure time of about $10^{-12}$ s. (From [50]).
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References


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Fig. 20. Diagram showing survival of cells subject to ionizing X-ray radiation from a laser-produced plasma and a conventional CW X-ray source. Similar survival curves are obtained for both sources. (From [57]).

exposure time of about 1 ps is illustrated in Fig. 19 for the case of a single-shot recording of one of the ear-bones, the Incus. For the recordings in both Figs. 18 and 19, medical image plates, which are much more sensitive than photographic plates and also re-usable were employed. The future for laser-produced X-rays in medicine will depend on the possibility to develop compact and efficient laser systems and gateable image plates. Recent experiments with a 1 kHz reasonable compact system gave encouraging results [56].

A very important aspect in the potential use of laser-produced X-rays is the demonstrate that these widely spaced extremely powerful X-ray spikes do not present an additional detrimental ionizing radiation effect for the same integrated Gray dose. A first experiment using V79 Chinese hamster cells showed that this does not seem to be the case (Fig. 20) [57].

4. Conclusions

As illustrated above, photonic interactions provide numerous possibilities for advanced diagnostics in the environmental as well as the medical field. Maybe somewhat unexpectedly, very similar concepts are used in both application areas, basically due to the fact that in both fields complex organic molecules are non-intrusively being studied using absorption, scattering or fluorescence. Optics provides through its spectroscopic capability possibilities for substance identification. The concept of multi-spectral imaging combined with advanced image processing allows the identification of pixels fulfilling a specified criterion (e.g., of being cancer) to be highlighted and superimposed on a normal colour image in real time. In this way a very attractive and intuitive interface to the human operator is provided.