PHOTOVOLTAICS

Solar-assisted cars

In the same month that Ferrari showed the world that it is going green — with the installation of 1,500 m^2 of solar panels on the rooftop of its production facility in Maranello, Italy, providing 213,985 kW h per year to help power its operations — Toyota revealed that solar panels will adorn the roof of the 2010 model of the Toyota Prius. Meanwhile, after-market manufacturers are providing solar kits for the Prius and other electric–petrol hybrids.

The Prius was launched in Japan in 1997, making it the first mass-produced hybrid vehicle, and was released worldwide in 2001. In May 2008, worldwide sales passed 1,000,000, with more than half of those sales in the United States. The solar panel used by Toyota is reportedly made by Kyocera and is used to power the car's climate control (including the air-conditioning motor), reducing the burden on the battery and petrol motor. The solar cells reportedly supply about 1 kW of power, which is enough to keep things cool, even while the car is parked out in the sunlight with its engine turned off. Additionally, the system (which is an optional extra) can be activated remotely from the key fob to start up the air conditioner before you get in the car.


TOYOTA

The idea of fitting cars with solar panels is not new, and after-market companies already provide solar kits for various hybrid vehicles including the Prius. For example, California-based Solar Electric Vehicles (SEV) has offered customized solar panels for the Prius roof since 1994. The panel can generate 215 watts of power and is manufactured from high-efficiency monocrystalline photovoltaic cells. The system, which takes only a few hours to install and has a cost-benefit break-even period of about 2–3 years, ultimately provides about 20 miles per day of electric driving range, resulting in a claimed improvement in fuel efficiency of about 29 per cent (depending on driving habits and conditions). Back in 1984, the founders of SEV actually developed the first car powered exclusively by solar energy with a 1.2-kW solar array, a 1-hp wheel motor and no batteries, which ran at speeds of up to 41 mph.

The new Prius is the first production car whose air conditioning can run on solar power alone. The big question is: will other car manufacturers follow suit, perhaps ultimately resulting in a completely solar-powered production car?

DAVID PILE

IMAGE TRANSMISSION

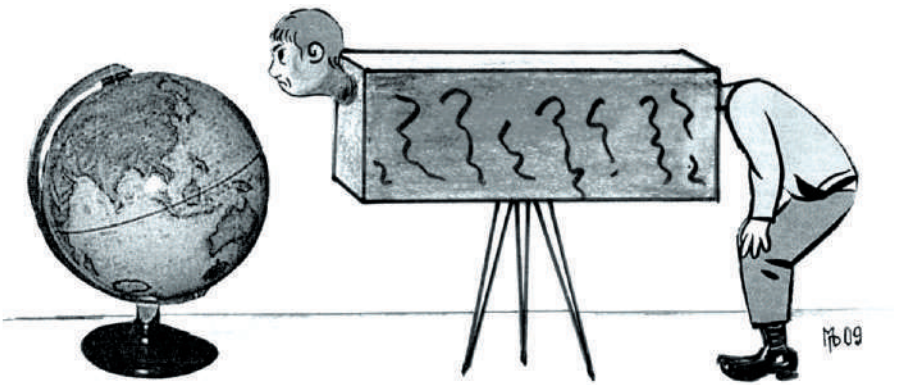
Looking into a self-distorting world

Imaging through linear media is straightforward, but light beams propagating through nonlinear media become heavily distorted, rendering all usual imaging techniques practically useless. Now, scientists have found a way to recover images transmitted through nonlinear media — by using back-propagation simulations.

Mordechai Segev and Demetrios N. Christodoulides

Light beams, and thus images, passing through nonlinear media are heavily distorted as they propagate because of a complex and dynamic interaction between light and matter. As a result, it is difficult to look through nonlinear media or to extract three-dimensional images from within the media. Is it possible to recover pictorial information transmitted through them? Yes, if information is not lost — radiated away or simply absorbed. Would we be able one day to look through such an environment, which is generically hostile to transmission of structured light beams? Or, better, could we look into such media and obtain three-dimensional images within the material? Here we describe the issues involved, review the historical evolution of the ideas, discuss the recent success, pose some non-trivial questions, and, we hope, provide some insight into the subject. On page 211 of this issue[1], Jason Fleischer and co-workers at Princeton University demonstrate a computational method of recovering images transmitted through a nonlinear medium. By measuring the output and numerically back-propagating the wave dynamics, they not only show that they can recover the input of two-dimensional spatial beams containing images, but also reconstruct the light field at intermediate points in the medium.

Nature is inherently nonlinear in its response to beams of light. Take a light beam, launch it through any medium and raise the intensity. At some point the beam will start modifying the properties of the medium, which will, in turn, modify the structure of the beam itself, causing further changes in the medium properties, which again change the beam pattern, in a dynamical fashion. In most material systems, nonlinear optical dynamics can occur by virtue of a variety of physical mechanisms. Examples range from ultrafast



MICHAEL POLONSKY, TECHNION

Figure 1 | Princeton scientist peeking through a nonlinear medium.

phenomena such as the optical Kerr effect and two-photon absorption, to fairly slow phenomena such as thermal 'blooming' and photorefractive effects. Some of these nonlinear effects (for example the optical Kerr effect) do not involve loss of optical power, whereas others (such as two-photon absorption) are lossy, causing higher losses in brighter regions with higher light intensity. Some of the effects are local in space, meaning that the change in material properties at any point is a function of the optical field at that point only; others are highly non-local, signifying long-range nonlinear effects. In all such nonlinear media, image-bearing optical beams are greatly distorted when the experimental parameters are deep in the nonlinear regime. For instance, if the medium is of the self-focusing type, brighter spots will become narrower and narrower, and broad regions of high intensity will fragment into pieces. Likewise, nonlinear interactions with noise give rise to a phenomenon known as 'modulation instability', which is essentially the spontaneous formation of patterns — a universal phenomenon that manifests itself very strongly as intricate patterns appear in optical beams. All of these physical mechanisms, and many more, distort optical beams passing through nonlinear media.

The subject of recovering optical information (images) borne on beams propagating in highly nonlinear media has attracted much attention since the early days of the laser, when thermal blooming was found to distort high-power beams. Naturally, one of the ways to avoid signal distortion is simply to reduce the intensity to the level where the medium behaves linearly. However, the truth is that high-intensity light has many advantages and is often desirable: for example, it raises the signal-to-noise ratio in signal propagation. The other argument is that nonlinearities do exist even at low intensities; they are just weaker. A good measure for identifying cases where nonlinear effects are significant is to calculate the nonlinear phase-shift — the product of vacuum wave number, nonlinear index change and propagation distance. Nonlinear effects become significant when this phase-shift is comparable to π. Hence, if the propagation distance is large enough, nonlinear effects are inevitable even at very low intensities.

Going back to the basic question, is it at all possible to recover optical information borne on beams propagating in highly nonlinear media? Not always. If information is lost, the process becomes irreversible, and one cannot recover the initial data. When the loss is linear, as in simple absorption, information embedded in weak wave components is lost when the intensities of such waves are weaker than the noise from scattering, material imperfections and such like. The problem becomes more severe when loss is nonlinear, for example in two-photon absorption, in which case the loss is greater at brighter spots, and the image will be distorted. Modulational instability is another example of such an irreversible process, as it is 'triggered' from random noise itself. Inherently, reversibility is a prerequisite for complete reconstruction of information. Hence, any process that leads to an irreversible entropy production imposes severe limitations on the ability to reconstruct information.

Historically, the first proposal of a method of transferring pictures through a nonlinear medium was made in 1977 by Yariv[2], who suggested using phase conjugation. A phase-conjugate mirror essentially creates a complete reflection of the optical field, but conjugates the spatial part of the phase. As such, a beam passed through any phase element, be it a simple lens or a complex distortion, then reflected off a phase-conjugate mirror and passed again through the phase element, would emerge after this round trip with its original information completely restored (provided all elements in the system are reciprocal: no apertures, for example). This idea works well for transmitting pictures through a multimode fibre and/or a reciprocal nonlinear medium without linear or nonlinear loss. Indeed, information retrieval by virtue of phase conjugation was demonstrated by Fischer's team in 1985 (ref. 3). But one could naturally ask: what is this good for, if one must send the information back and forth? Indeed, just for information transmission, the idea, nice as it may be, is of little value. However, using 'passive' (self-pumped) phase-conjugate mirrors in this fashion does provide an excellent system for interferometry and accurate distance sensing through distorting media[3,4]. Likewise, using a phase-conjugate mirror to replace a laser mirror improves the performance of the resonator considerably.

Over the years, there have been several attempts to develop methods for image transmission through nonlinear media. Some ideas have to do with various schemes of forward four-wave mixing[5,6], which are similar to phase conjugation but do not require round-trip propagation. But all these methods offer very limited solutions: either the medium must be 'short' so that the accumulated nonlinear phase shift is small, or the spatial resolution is very limited. Some particular nonlinear systems have been found to be amenable to system-specific solutions, an example being electromagnetically induced transparency[7], albeit thus far with rather limited resolution. But these are all material-specific and cannot solve the general problem of imaging through a nonlinear medium.

In 2001, a more general method was demonstrated, offering a means of transferring images through non-instantaneous nonlinear media[8]. That idea relies on using the image-bearing optical beam to induce a highly multimode incoherent soliton, which contains information related to the image embedded in its modal amplitudes and phases. Alternatively, one can use the multimode waveguide that the soliton induces in the medium, and transmit a weak image-bearing beam through this waveguide, through which the propagation is linear[8]. The idea works, but it requires that the nonlinearity is non-instantaneous (that is, the modal phases fluctuate independently much faster than the response time of the nonlinear medium). As such, this method is not universal. More recently, the transmission of incoherent solitons in highly non-local yet temporally instantaneous nonlinear media has been demonstrated, and these too can be used to carry pictorial information through nonlinear media[9]. But again, the method is restricted to non-local nonlinearities.

What Fleischer and co-workers demonstrate[1] is a universal method that is not material-specific. It relies on the characterization of the nonlinear medium (form of nonlinearity, parameters, propagation distance and so forth), detection of the amplitude and phase of the light emerging from it, and subsequently simulation of the back-propagated light in the medium and retrieval of the input information. They record the amplitude of the light field containing image information using a CCD (charge-coupled device) and capture the phase based on interference (holographic) measurement. Light propagation is described by the nonlinear (Schrödinger-like) wave equation and beam evolution is calculated numerically by the Fourier split-step method. Clearly, the idea works rather well, leading to a resolution of around 10 μm (50 optical wavelengths within the medium) which is mainly restricted by the non-ideal properties of the nonlinear crystal used. The resolution could be improved in materials that are more homogeneous (without defects or striations) and whose nonlinearity can be better characterized.

This back-propagation method has in fact been demonstrated in the past in a one-dimensional physical setting to recover the structure of ultrashort temporal pulses propagating in optical fibres[10]. More recently, it has successfully been introduced in wavelength-division multiplexing fibre systems used for optical communication, as a means of compensating for undesirable dispersive and nonlinear transmission effects[11]. The computational requirements for post-compensation of distributed nonlinearity were also discussed[11]. Fleischer and colleagues have now introduced the idea into the spatial domain and successfully handled the additional complexity incurred by the higher dimensionality. They extended the method from one-dimensional temporal pulses to two-dimensional pictures and were also able to recover the entire beam dynamics as the beam evolves in the third dimension (the propagation direction).

Clearly, universality is the merit of the approach by Fleischer and co-workers. But from a technological standpoint, it has one important limitation: long computation time, especially in the spatial domain. The computation time for transferring two-dimensional pictures through a nonlinear medium is considerable. It is not obvious whether the method is fast enough to be used for transmitting images at video rates through a fast-responding nonlinearity. Nevertheless, the intrusion of the ideas and algorithms in data processing into the highly nonlinear domain does signify a step forward in image processing. We certainly envisage that, in the future, it would be possible to transmit pictorial information through nonlinear media at high data rates.

Can such techniques also provide information about evanescent waves that decay, by tracking them through their nonlinear coupling to propagating waves, as suggested by Fleischer and co-workers? That is another question worth pondering, because the nonlinear coupling from evanescent waves to propagating waves would have to dominate over the nonlinear coupling with noise (modulation instability), which is thermodynamically irreversible. On this question, the jury is still out. ❐

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MAGNETO-OPTICS

Hot atoms rotate light rapidly

The ability to harness the Faraday effect on a short timescale in an ensemble of hot atoms may prove useful as a read-out tool for quantum information based on microscale vapour cells.

Robert Löw and Tilman Pfau

"Work. Finish. Publish." This advice from the English physicist and chemist Michael Faraday (Fig. 1) is just as appropriate today as when it was first coined in the nineteenth century. In 1845, his determined research led him to one of his most important discoveries. Faraday observed that a magnetic field could rotate the polarization of light in one of his homemade high-index 'heavy' glasses, and that the magnitude and direction of the rotation were dependent on the strength and direction of the magnetic field respectively.

Today the Faraday effect is a phenomenon routinely used in all optics laboratories. Crystals such as borosilicate glasses or garnet crystals, which show a strong effect, are commonly used to build diodes for light, called optical isolators. The Faraday effect is also active and well studied in atomic gases. Here the most prominent application is magnetometry[1], where the polarization rotation can be used to measure small magnetic fields with a sensitivity of a few fT $\mathrm{Hz}^{-1/2}$ with a measurement bandwidth of up to 1 kHz, sufficient for detecting human cardiomagnetic fields[2]. These gaseous sensors require narrow spectral features for best performance, and ideally one would like to use weakly interacting laser-cooled atoms to avoid any unwanted broadening effects. As a result, much current research is devoted to studying colder and colder atoms, and narrower and narrower spectral features.

In contrast, on page 225 of this issue Paul Siddons and colleagues from Durham University[3] point out that the Faraday effect is actually a powerful tool in hot atomic gases for applications requiring large measurement bandwidth — that is, for measuring fast dynamics within the gas or the dynamics of external fields. The authors observe large Verdet constants (the measure of the strength of the Faraday