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MEASUREMENT TECHNIQUES USED FOR ULTRAFAST PULSES IN OPTICS

Bablu Kumar Singh[1],Pradeep Kumar Sharma[2],Abhinav Lohiya[3] ,Deepak Mathur[4]
[1,3,4]Assistant Professor, [2]M.Tech Scholar, Department of ECE
Jodhpur Institute of Engineering and Technology
Jodhpur, India
bablukumar.singh@gmail.com[1],pradeep_jiet@yahoo.com[2]
abhinav.lohiya@jietjodhpur.com[3],deepak.mathur@jietjodhpur.com[4]

***Abstract*—In optics, an ultra-short pulse of light is an electromagnetic pulse whose time duration is of the order of a femtosecond. Such pulses have a broadband optical spectrum, and can be created by mode-locked oscillators. This paper describes the development of ultrafast optics, describes its system application, and suggests various measurement techniques.**

Keywords*—Ultrafast pulses, optics, mode-locked oscillators.

I. INTRODUCTION

The term ultrashort refers to the pulses which range from femtosecond to picoseconds, although these pulses no longer hold the record for the shortest pulses artificially generated. Indeed, x-ray pulse having duration of the attosecond time scale have been reported. They are also called as ultrafast events. Amplification of ultrashort pulses almost always requires the technique of chirped pulse amplification, in order to avoid damage to the gain medium of the amplifier. They are characterized by high peak intensity (or more correctly, irradiance that usually leads to nonlinear interactions in various materials, including air. These processes are studied in the field of nonlinear optics. The 1999 Nobel Prize in Chemistry was awarded to Ahmed H. Zewail for using ultrashort pulses to observe chemical reactions on the timescales they occur on, opening up the field of femtochemistry

Although optical devices are also used for continuous light, like beam expanders and spatial filters may be used for ultrashort pulses. Several optical devices have been specifically designed for ultra short pulses. One of them is the pulse compressor, a device that can be used to control the spectral phase of ultrashort pulses. It is composed of a sequence of prisms, or gratings. When properly adjusted it can alter the spectral phase φ(ω) of the input pulse so that the output pulse is a bandwidth-limited pulse with the shortest possible duration. A pulse shaper can be used to make more complicated alterations on both the phase and the amplitude of ultrashort pulses.

To accurately control the pulse, a full characterization of the pulse spectral phase is a must in order to get certain pulse spectral phase (such as transform-limited). Then, a spatial light modulator can be used in the 4f plane to control the pulse. Multiphoton Intrapulse Interference Phase Scan (MIIPS) is a technique based on this concept. Through the phase scan of the spatial light modulator, MIIPS can not only characterize but also manipulate the ultrashort pulse to get the needed pulse shape at target spot (such as transform-limited pulse for optimized peak power, and other specific pulse shapes). This technique features with full calibration and control of the ultrashort pulse, with no moving parts, and simple optical setup.

II. ULTRAFAST MEASUREMENT TECHNIQUES

Several techniques are available to measure ultrashort optical pulses:

- Intensity autocorrelation: gives the pulse width when a particular pulse shape is assumed.
- Spectral interferometry (SI): a linear technique that can be used when a pre-characterized reference pulse is available. Gives the intensity and phase. The algorithm that extracts the intensity and phase from the SI signal is direct.
- Spectral phase interferometer for direct electric-field reconstruction (SPIDER): a nonlinear self-referencing technique based on spectral shearing inter-ferometry. The method is similar to SI, except that the reference pulse is a spectrally shifted replica of itself, allowing one to obtain the spectral intensity and phase of the probe pulse via a direct FFT filtering routine similar to SI, but which requires integration of the phase extracted from the interferogram to obtain the probe pulse phase.
- Frequency-resolved optical gating (FROG): a nonlinear technique that yields the intensity and phase of a pulse. It's just a spectrally resolved autocorrelation. The algorithm that extracts the intensity and phase from a FROG trace is iterative.
- Grating-eliminated no-nonsense observation of ultrafast incident laser light e-fields (GRENOUILLE), a simplified version of FROG.

1. *Pump Probe Measurements*

A. *Non-Collinear Pump-Probe Measurement:*

To suppress background light and low frequency noise of the probe beam the pump beam is chopped. Ideally, the chopper frequency is chosen large enough to enable shot noise limited detection. Sometimes the test devices or samples have a rough surface and pump light scattered from the surface might hit the detector. This can be partially suppressed by orthogonal pump and probe polarization. This is a standard technique to understand relaxation dynamics in condensed matter, such as carrier relaxation processes in semiconductors.

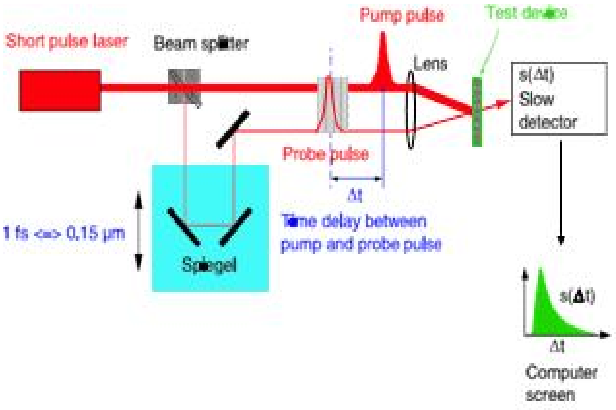

Fig. 1. Pump-probe setup to extract time constants relevant for the carrier dynamics in semiconductors

B. *Colinear Pump-Probe Measurement:*

Sometimes pump and probe pulses have to be collinear, for example when pump probe measurements of waveguide devices have to be performed. Then pump and probe pulse, which might both be at the same center wavelength have to be made separable. This can be achieved by using orthogonal pump and probe polarization or by chopping pump and probe at different frequencies and detecting at the difference frequency.

2. *Heterodyne Pump Probe*

The lock-in detection is greatly improved if the difference frequency at which the detection occurs can be chosen higher and the signal can be filtered much better using a heterodyne receiver.Here AOM's are used to prepare a probe and reference pulse shiftet by 39 and 40 MHz respectively. The pump beam is chopped at 1kHz. After the test device the probe and reference pulse are overlayed with each other by delaying the reference pulse in a Michelson-Interferometer.

If an AM or FM receiver is used and the interferometers generating the reference and probe pulse are interferometerically stable, both amplitude and phase nonlinearities can be detected with high signal to noise.

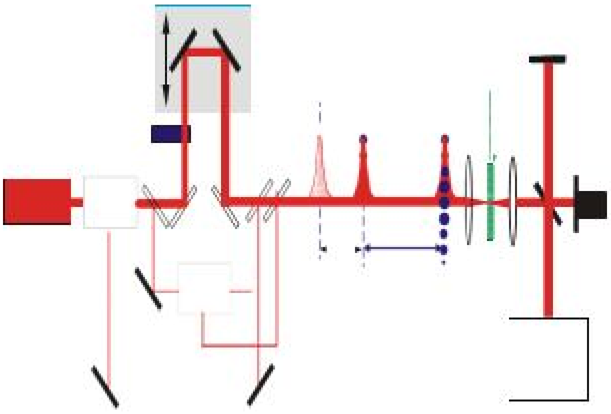

Fig. 2. Heterodyne pump probe using AM and FM receiver to detect amplitude and phase nonlinearities

3. *Electro -Optic Sampling:*

Electro-Optic Sampling was invented by Valdmanis and Mourou in the early 1980's. Its is based on polarization rotation of a short laser pulse when propagating in a medium showing a linear electro-optic effect. The polarization rotation is due to an applied electric filed, i.e. the optical pulse samples the instantaneous electric field.

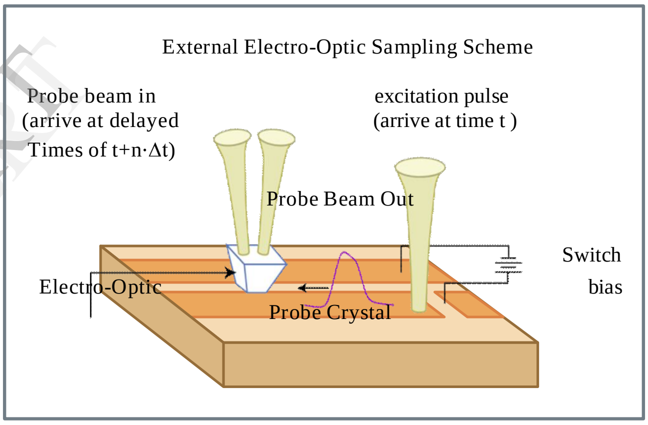

Fig. 3. *Electro-optic sampling*

3.1 Applications

- It is particularly important for the characterization of high-speed electronic components, e.g. microwave circuits, ultrafast transistors ,photo detectors , and transmission lines. In this area, it is applied e.g. in ultrafast sampling oscilloscopes with bandwidths of several terahertz.
- Terahertz waveforms can be measured with electro-optic sampling, and terahertz spectroscopy can be performed, e.g. comparing the spectra of terahertz pulses before and after passing through a sample.

- Even non-synchronized electro-optic sampling can be useful, e.g. for obtaining optical spectra of mid-infrared, far-infrared or terahertz sources

3.2 Types of Electro-optic Probes

In internal electro-optic sampling (or direct electro-optic sampling), the substrate e.g. of an integrated circuit is used as the electro-optic medium. Of course, the substrate has to be an electro-optic material in that case. Suitable substrates are gallium arsenide (GaAs) and indium phosphide (InP). Internal sampling is minimally invasive.

In external electro-optic sampling (or indirect electro-optic sampling), one uses an external electro-optic probe (proximity electrodeless modulator). This probe may be a plate of electro-optic material (used in transmission or reflection) or a small (micromachined) crystal, which may be mounted on a fiber (often with a GRIN lens in between). Often used crystal materials are lithium tantalate ($LiTaO_3$), bismuth silicate (BSO), zinc telluride (ZnTe), and gallium arsenide (GaAs). GaAs is favorable owing to its high electro-optic coefficient, its capability to be micromachined (with mechanical or chemical methods), and its relatively small dielectric constant (reducing back action on the sample). Invasiveness of electro-optic probes is often a considerable concern, as the use of an electro-optic probe with high dielectric constant can cause time delays and reflections in the device under test.

3.3 Types of Electro-optic Sampling Systems

Pump–probe systems use two copies of optical pulse trains with a variable time delay. Mechanically changing the time delay allows sequential sampling of different portions of a waveform. The timing jitter of the mode-locked laser is not important, as only the relative timing between pump and probe pulses matters, and these pulses are derived from the same laser pulses. Other systems use a single pulse train which is synchronized to an electronic (often microwave) oscillator. Here, the sequential sampling is achieved by introducing a small frequency offset between some harmonic of the pulse repetition rate and the electronic oscillator which drives the device under test.

4. *THz Spectroscopy and Imaging*

Terahertz spectroscopy detects and controls properties of matter with electromagnetic fields that are in the frequency range between a few hundred gigahertz and several terahertz (abbreviated as THz). In many-body systems, several of the relevant states have an energy difference that matches with the energy of a THz photon. Therefore, THz spectroscopy provides a particularly powerful method in resolving and controlling individual transitions between different many-body states. By doing this, one gains new insights about many-body quantum kinetics and how that can be utilized in developing new technologies that are optimized up to the elementary quantum level.

Different electronic excitations within semiconductors are already widely used in lasers, electronic components, computers, to mention a few. At the same time, they constitute an interesting many-body system whose quantum properties can be modified, e.g., via a nanostructure design. Consequently, THz spectroscopy on semiconductors is relevant in revealing both new technological potentials of nanostructures as well as in exploring the fundamental properties of many-body systems in a controlled fashion.

In optical spectroscopy, the detectors typically measure the intensity of the light field rather than the electric field because there are no detectors that can directly measure electromagnetic fields in the optical range. However, there are multiple techniques, such as antennas and electro-optical sampling, that can be applied to measure the time evolution of $E_{THz}(t)$ directly. For example, one can propagate a THz pulse through a semiconductor sample and measure the transmitted and reflected fields as function of time. Therefore, one collects information of semiconductor excitation dynamics completely in time domain, which is the general principle of the terahertz time-domain spectroscopy.

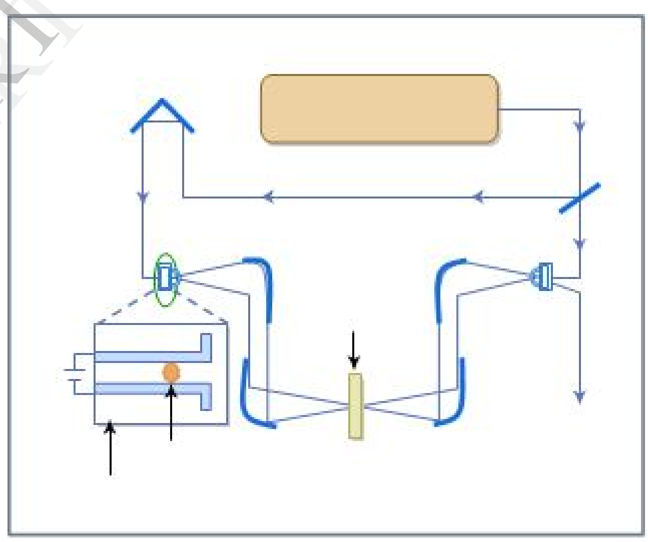

Fig. 4. *THz Time Domain Spectroscopy*

5. *Four-Wave Mixing*

A more advanced ultrafast spectroscopy technique than pump-probe is fourwave mixing (FWM). It enables to investigate not only energy relaxation processes, as is the case in pump-probe measurements, but also dephasing processes in homogenous as well as inhomogenously broadened materials.

Four-wave mixing is an intermodulation phenomenon in non-linear optics, whereby interactions between two wavelengths produce two extra wavelengths in the signal. It is similar to the third-order intercept point in electrical systems. Four-wave mixing can be compared to the intermodulation distortion in standard electrical systems. When three frequencies (f1, f2, and f3) interact in a nonlinear medium, they give rise to a fourth wavelength (f4) which is formed by the scattering of the incident photons, producing the fourth photon. With the most damaging signals to system performance calculated as fijk= fi + fj – fk, since these frequencies will lie close to one of the incoming frequencies. From calculations with the three input signals, it is found that 12 interfering frequencies are produced, three of which lie on one of original incoming frequencies. Four-wave mixing (FWM) is also present if only two components interact. In this case the term

F0=f1 +f1 –f2, couples three components, thus generating so-called degenerate four-wave mixing, showing identical properties as in case of three interacting waves.

FWM is a fiber-optic characteristic that affects wavelength-division multiplexing (WDM) systems, where multiple optical wavelengths are spaced at equal intervals or channel spacing. The effects of FWM are pronounced with decreased channel spacing of wavelengths and at high signal power levels. High chromatic dispersion decreases FWM effects, as the signals lose coherence. The interference FWM caused in WDM systems is known as inter-channel crosstalk. FWM can be mitigated by using uneven channel spacing or fiber that increases dispersion

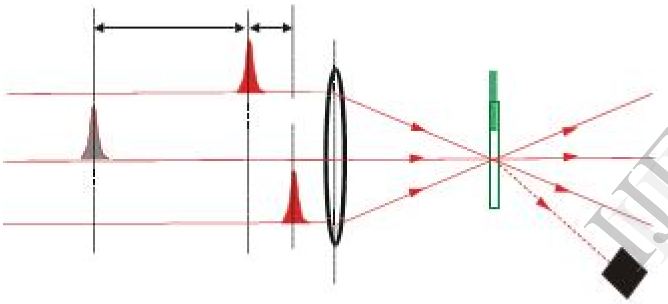

Fig. 5. *Typical Four-Wave-Mixing (FWM) beam geometry.*

III. APPLICATION OF ULTRAFAST OPTICS

Various applications of ultra fast optics are:

- Micro-machining
- Frequency comb: A frequency comb is a light source whose spectrum consists of a series of discrete, equally spaced elements. Frequency combs can be generated by a number of mechanisms, including amplitude modulation of a continuous wave laser or stabilization of the pulse train generated by a mode locked laser. A frequency comb allows a direct link from radio frequency standards to optical frequencies. Current frequency standards such as separate in the microwave region of the spectrum, and the frequency comb brings the accuracy of such clocks into the optical part of the electromagnetic spectrum. A simple electronic feedback loop can lock the
- Femtochemistry
- Medical imaging: Ultrashort laser pulses are used in multiphoton fluorescence microscopes
- Medical Surgery:
- High time resolution: Ultrafast Spectroscopy, tracing of ultrafast physical processes in condensed matter , chemical reactions physical and biological processes, influence chemical reactions with femtosecond pulses: Femto-Chemistry (Noble Prize, 2000 to A. Zewail), high speed electric circuit testing and sampling of electrical signals,
- Terahertz (T-rays) generation and detection.
- Repetition rate to a frequency standard.
- High spatial resolution: optical imaging, e.g. optical coherence Tomography
- Imaging through strongly scattering media
- High bandwidth: massive WDM - optical communications, many channels from one source or massive TDM, high bit-rate stream of short pulses.
- High intensities: Large intensities at low average power : Nonlinear frequency conversion, laser material processing, surgery, high intensity physics: x-ray generation, particle acceleration

IV. CONCLUSION AND FUTURE PROSPECTS

Ultrafast optics pushes the frontiers of

- *Telecommunications:* Pico second pulses allow up to 100-Gbit/s transmission rate, which can be multiplied by several orders of magnitude in hundreds of WDM channels to result in transmitting multi-Terabit information per second through one single optical fibre over thousands of kilometres.
- *Industrial and biological-medical technologies & instrumentation:* ultrashort-pulsed laser sources have dramatically improved the resolution of optical microscopy (from sub-micrometers to the ten nanometre range with visible light: diffraction limit is vastly overcome by exploiting optical nonlinearities!); provide the only means of machining and structuring materials with nanometre precision (nanophotonics); offer new diagnostic and therapic tools for medicine.
- *Frequency and time metrology*: the equidistant spectral lines of a stabilized femtosecond laser can form a “frequency ruler” of unprecedented simplicity and precision, constituting“clockwork” for referencing frequency measurements to the Caesium frequency standard and paves the way towards a much more accurate optical frequency clock.

- *Ultrafast metrology*: the resolution limit (dictated the probing pulse duration) of ultrafast optics surpasses that of the fastest electronic devices by several thousand times ;at the frontier of ultrafast science, attosecond metrology allows to observe the motion of electrons on atomic length scales in real time and record the electric field of visible light
- *High-field science:* focused gigawatt-terawatt-petawatt light pulses are able to expose matter to unprecedented electric fields ranging from billion to trillion V/cm; these field strengths ionize matter instantly, accelerate electrons to relativistic speeds within micrometers and pave to way towards compact laboratory-scale particle accelerators .
- *Coherent light sources:* by inducing polarisation that depends nonlinearly on the driving light field, femtosecond lasers allow creating powerful sources of coherent light in wavelength ranges where no efficient laser sources are available; femtosecond-laser-driven coherent light sources now cover the wavelength range of ~1 mm – 1 nm (frequency: 0.3 Thz – 300 phz), all the way from the far infrared to the regime of soft x-rays! With femtosecond-laser-accelerated electrons even a laboratory source of coherent hard x-rays (~0.1 nm) may become possible.
- *Intense laser pulses* interacting with solid surfaces can create energetic plasmas for research into numerous areas, for example: inertial confinement fusion; compact particle accelerators; radiation sources; scaled astrophysical experiments.

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