INVITED PAPER

Ultrafast electrical signal generation, propagation and detection

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Received 5 December 1995; revised 23 February; accepted 27 February 1996

Short-pulse optical sources have allowed the study of ultrafast electrical phenomena in the circuits and devices which will become future electronic systems. In this paper techniques for the generation, propagation and detection of electrical signals in the femtosecond regime are presented.

1. Introduction

Short-pulse laser sources are routinely available in the femtosecond regime. These optical pulses can be converted into electrical pulses through a variety of techniques, resulting in femtosecond electrical pulses. The electrical pulses can be detected by various means using the same laser source, realizing a jitter-free sampling oscilloscope. This has allowed major advances in the study of electrical phenomena in fields ranging from materials characterization to device physics and non-linear optics in the submillimetre regime.

In this paper techniques available for the (optical) detection of ultrafast electrical signals with a time resolution down to 200 fs are presented. Various methods for optical generation of picosecond and subpicosecond electrical pulses are then discussed. The last part of this paper will deal with modelling, measuring and optimizing the propagation of these pulses on coplanar transmission lines. The authors start with a brief introduction of commonly used optical sources.

2. Ultrafast laser sources

2.1. Dye lasers

Until recently, the standard tool for ultrafast electrical measurements has been the colliding-pulse mode-locked (CPM) laser [1]. This is a continuous wave (CW) pumped dual-dye laser which is passively mode locked due to the interplay between saturable absorption and saturable gain. The gain and absorber dyes limit operation to ~620 nm and ~20 mW with a period of ~10 ns (frequency ~100 MHz). Through the use of intracavity prisms, group velocity
dispersion can be partially compensated resulting in optical pulses as short as 27 fs full-width at half-maximum (FWHM) directly from the oscillator [2]. For stability reasons, the pulse width used for most measurements reported here is ~100 fs FWHM [3]. Noise in this laser can be 25 ps root mean square (r.m.s.) in a 1 kHz bandwidth [4], although active feedback stabilization of the cavity length can reduce this by more than an order of magnitude [4, 5]. Amplification to the μJ pulse⁻¹ level provides sufficient intensities to induce self-phase modulation allowing optical pulse compression to 8 fs using a fibre-grating system [6] or 6 fs using a fibre-grating–prism system [7].

2.2. Solid-state lasers
Recent development of the Ti-doped sapphire (Ti : Al₂O₃ or Ti : sapphire) [8] laser has allowed pulses to be produced that are as short as ~11 fs FWHM, 0.5 W at 817 nm and with noise spectra that are quieter than the CPM [9]. Periods are generally ~12 ns (frequency ~80 MHz). The noise reduction is due to the operation without dye jets, which are required in the CPM laser. The lasing bandwidth of Ti : sapphire is sufficient to support a pulse as short as ~3 fs, although higher-order group velocity distortion becomes problematic for pulses ≤10 fs [10]. Typical pulse widths are anywhere from ≪50 to ~150 fs, depending on the exact configuration of the cavity. This laser can operate mode-locked above and below the band edge for semiconductors like GaAs (~870 nm), and so can be operated as either a pump or a probe. Recent versions have demonstrated two-colour operation making excitation above and probing below the bandgap energy available simultaneously [11–13]. Lower repetition rate amplifiers can achieve terawatt peak powers using chirped pulse amplification [14, 15], where optical non-linearities in semiconductors become important.

3. Electrical pulse generation – photoconductive switching
In order to use these fast optical pulses to study electronic circuits it is necessary to make a transition from the optical to the electrical regime. When an optical pulse is incident on the surface of a semiconductor, the optical energy is absorbed to form free electrons and holes. In materials like GaAs the hole mass is about ten times larger than the electron mass, so that only electron dynamics are considered for short times. If the carrier lifetime is much less than the laser repetition rate, it is sufficient to form a photoconductive switch (PCS) [16]. The switch consists of a gap in a metal electrode on the surface of a semiconductor. For highly resistive, i.e. low dark current, material, a large voltage applied to one side of the gap will be isolated from the other. When the laser pulse illuminates the gap, the carriers generated will effectively short the gap, causing a voltage to appear on the other side of the gap. The carrier generation process can be viewed as instantaneous, so the measured voltage rise-time is a measure of the system response; while the fall-time of this pulse is determined by the carrier recombination time, which for materials like semi-insulating (SI) GaAs or InP is ~100 ps. Unfortunately, for Si this time is ~1 μs, making it too long compared to the laser repetition rate of 10–12 ns. A photoconductive switch can be regarded as a time-dependent voltage divider. For a gapless [17] or sliding contact [18] switch with a given bias voltage, V₀, the voltage, V(t), is divided between the characteristic impedance of the transmission line, Z₀, and the time-dependent impedance of the semiconductor in the switch, Rₛ(t), with contact resistance Rₖ [19]:

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V(t) = V₀ \frac{Z₀}{Z₀ + Rₛ(t) + Rₖ}
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