A reprint from

OPTICAL ENGINEERING

November 1996

ISSN 0091-3286

SELECTING A SHORT-PULSE LASER SYSTEM FOR PHOTOCONDUCTIVE GENERATION OF HIGH-SPEED ELECTRICAL PULSES

Nicholas G. Paulter

Selecting a short-pulse laser system for photoconductive generation of high-speed electrical pulses

Nicholas G. Paulter
National Institute of Standards and Technology
Electricity Division
Gaithersburg, Maryland 20899
E-mail: paulter@nist.gov

Abstract. The selection of a short-pulse laser is important in electrical pulse metrology applications where the electrical pulses are generated photoconductively. Not only is the duration of the generated electrical pulse important, but so is the peak amplitude of that pulse. Insufficient pulse amplitude may cause excessive uncertainty in measurement results. An approximation is presented that can provide guidelines to selecting the optimal short-pulse laser according to photoconductor, laser, and measurement system characteristics.

Subject terms: photoconductive electrical pulse generation; short-duration electrical pulse; short-pulse laser.

Paper 31026 received Feb. 22, 1996; revised manuscript received June 3, 1996; accepted for publication June 4, 1996.

1 Introduction

Fast photodetectors are used for high-speed electrical-pulse generation in conjunction with short-pulse lasers and for monitoring the optical pulses from short-pulse laser systems. In both cases, the generated electrical pulse will be observed using an instrument having a bandwidth different from that of the generated electrical pulse. For monitoring short-pulse laser systems, this bandwidth difference does not create a problem, since typically the observation of an electrical-pulse representative of the optical pulse is sufficient. However, for pulse generation, specific electrical characteristics of the observed electrical pulse are sought, such as peak amplitude and pulse width. It is important to know what characteristics a short-pulse laser system must possess to generate an electrical pulse that allows the desired electrical behavior to be observed. An important application for high-speed pulse generation is the measurement of the impulse response of high-speed electrical test instrumentation, such as an oscilloscope.[1] The effect of oscilloscope bandwidth, photodetector response, and laser pulse width must be considered when selecting a laser system for generating electrical pulses that will be used to determine the impulse response of electrical test instrumentation: lasers producing the shortest-duration optical pulses may not be the optimal solution. Related analyses have been performed elsewhere; see Ref. 2, for example. In Ref. 2, the authors are primarily interested in the effect of interdigitated electrodes on photoconductor response and consider transient effects lightly, whereas here the primary concern is the effect of the transient characteristics of the optical pulse and photoconductor and oscilloscope responses on the observed photogenerated electrical pulse. The purpose of this paper is to provide engineers and scientists who are interested in using ultrafast photodetectors and short-pulse lasers for generating short-duration electrical pulses, but who do not have the requisite background or experience, with a basic understanding of the interplay between optical-pulse parameters and detector and recorder (oscilloscope) responses.

A laser parameter $E_{p,m}$ will be defined that can be used to provide a measure of the acceptability of a given short-pulse laser for photoconductive electrical-pulse generation, a process first observed about twenty years ago[3] and that has been observed in many semiconductor materials since.[4–8] The value of $E_{p,m}$ is calculated for a given photoconductor (PC) design and measurement condition (oscilloscope impedance, applied voltage, etc.) and is the minimum optical-pulse energy required to observe an electrical pulse having a peak voltage amplitude of at least V_m on an oscilloscope of impedance magnitude Z_0. The value of $E_{p,m}$ will be compared with the actual pulse energy E_p available for a given laser system.

The procedure for finding $E_{p,m}$ starts with an examination of the maximum PC on-state resistance, R_{on}, that will allow the desired pulse amplitude to be observed on an oscilloscope. This result is based on simple circuit theory. The value of R_{on} is also calculated from a physical description of a parallelepiped-shaped resistor of resistivity ρ. These two results for R_{on} are then equated to obtain an expression for the maximum carrier concentration, n_m, in the pulse-illuminated PC. The formula for n_m is then derived from quantum-mechanical principles, and the two results for n_m are equated to obtain an expression for $E_{p,m}$.

2 Analysis

We will apply a dc voltage V_a across the PC gap of width L (see Fig. 1). This electric field across the PC gap, V_a/L, must be less than that which can cause surface breakdown in the PC. The voltage $V(t)$ observed on an oscilloscope is given by

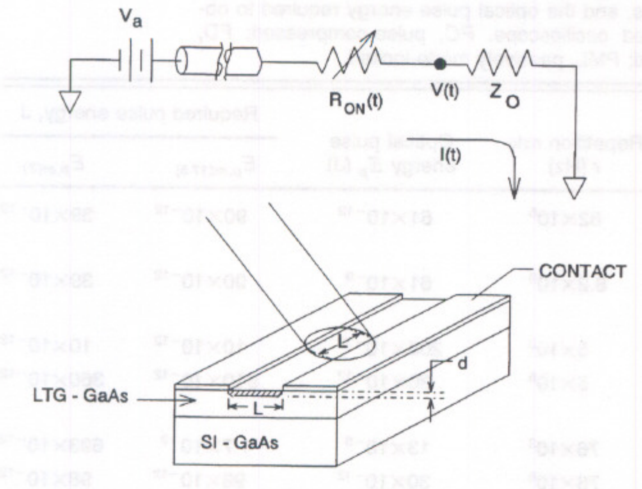


Fig. 1 Schematic of illuminated photoconductor and circuit diagram for measurement of the impulse response of an oscilloscope of impedance Z_0 using a photoconductor acting as a light-controlled resistor of resistance R_{on}.

$$V(t)=I(t)\ *\ h(t)Z_0, \tag{1}$$

where Z_0 is the impedance of the oscilloscope, $I(t)$ is the current through the circuit, $*$ indicates a convolution, and $h(t)$ is the impulse response of the oscilloscope. For the purposes here, we will assume an approximation to $h(t)$, because we may not know it accurately. The approximation is Gaussian-shaped pulse having unit area (integrates to one) and thus having no net loss or gain:

$$h(t)=\frac{1}{\sqrt{2\pi}kt_S}\exp[-t^2/2(kt_S)^2], \tag{2}$$

where t_S is the full width at half maximum (FWHM) of the Gaussian-shaped pulse, and k is a constant such that the product kt_S equals the characteristic or variance associated with the Gaussian function. The Gaussian approximation for $h(t)$ and other functions is used because laser pulse profiles are typically described by Gaussian or hyperbolic-secant-squared functions and using one type of function for the oscilloscope response, PC response, and laser pulse shape simplifies the equations that are to be presented. The function $I(t)$ can be described by

$$I(t)=\frac{V_a/2}{R_{\text{on}}(t)+Z_0}, \tag{3}$$

where $R_{\text{on}}(t)$ is the on-state resistance of the PC,

$$R_{\text{on}}(t)=\rho(t)\frac{L}{Ld}. \tag{4}$$

In (4), we have assumed in this approximation that the width L of the PC gap is uniformly illuminated over a length L. In reality, however, the area and uniformity of illumination will be dependent on the beam intensity profile, the focusing optics, and the distance between the PC and the focal plane of the focusing optics. The number 2 in Eq. (3) comes from the fact that, when R_{on} goes to zero and a length of transmission line is placed between the PC and the battery, the PC will launch an impulse having an amplitude $V_a/2$ in the direction of the load and $-V_a/2$ in the direction of the source.[9] The quantity d is the light absorption depth (a characteristic of the material), and $\rho(t)$ is the resistivity of the PC, given by

$$\rho(t)=\frac{1}{q\{\mu_n[n_0+n(t)]+\mu_p[p_0+p(t)]\}}\approx\frac{1}{q\mu_n n(t)}, \tag{5}$$

where μ_n and μ_p are the electron and hole mobilities, n_0 and p_0 are the intrinsic electron and hole concentrations, $n(t)$ and $p(t)$ are the optically generated electron and hole concentrations, and q is the electronic charge. Since we are interested in high-speed performance, we will consider low-temperature-grown (LTG) GaAs (Ref. 10) as the material of choice for this application. For bulk GaAs, $\mu_n=8500\ \text{cm}^2/(\text{V s})$ and $\mu_p=400\ \text{cm}^2/(\text{V s})$ (Ref. 11), and if we assume this relationship holds for LTG GaAs, then the hole contribution in Eq. (5) can be ignored in this approximation. In the approximation, we also assume $n(t) \gg n_0$. Using the approximation (5) in Eq. (4), and then Eq. (4) in Eq. (3), gives

$$I(t)=\frac{V_a/2}{1/q\mu_n n(t)d+Z_0}$$
$$\approx\frac{q\mu_n n(t)dV_a}{2} \tag{6}$$

for $q\mu_n n(t)dZ_0 \ll 1$, as is true for $Z_0=50\ \Omega$. The function $n(t)$ in Eq. (6) is described by a convolution of the optical pulse profile and the PC response function, which can be described by[12]

$$n(t)=\frac{n_\lambda}{\sqrt{2\pi}kt_L}\exp\left[-\frac{t^2}{2(kt_L)^2}\right]*r_0\exp\left[-\frac{t^2}{2(kt_R)^2}\right]$$
$$=n_\lambda r_0\frac{t_R}{(t_R^2+t_L^2)^{1/2}}\exp\left[-\frac{t^2}{2k^2(t_L^2+t_R^2)}\right], \tag{7}$$

where n_λ is the number of photons in the optical pulse, t_L is the FWHM of the laser pulse, t_R is the FWHM of the PC response function, and r_0 is the PC response-function coefficient. [Equation (7) could have been simplified if we had assumed that the photoconductor response was instantaneous,[13] that is, it did not integrate the photoconductively generated electrical charge.]

Using Eqs. (7), (6), and (2) in Eq. (1) gives

$$V(t)=\frac{q\mu_n n_\lambda r_0 dZ_0V_a}{2}\frac{t_R}{(t_R^2+t_L^2+t_S^2)^{1/2}}$$
$$\times\exp\left[-\frac{t^2}{2k^2(t_R^2+t_L^2+t_S^2)}\right]. \tag{8}$$

The maximum observed signal, V_m, occurs at $t=0$:

Table 1 Selected lasers, their pertinent characteristics, and the optical pulse energy required to observe the desired electrical pulse with the specified oscilloscope. PC, pulse-compressed; FD, frequency-doubled; AT, attenuated; PS, pulse-selected; PML, passively mode-locked.

Laser	Average power (W)	Wavelength λ (m)	Pulse width t_L (s)	Repetition rate r (Hz)	Optical pulse energy E_p (J)	Required pulse energy, J $E_{p,m(17.5)}$	$E_{p,m(7)}$
Nd:YAG, PC, FD, AT	5×10^{-3}	532×10^{-9}	3×10^{-12}	82×10^{6}	61×10^{-12}	90×10^{-12}	39×10^{-12}
Nd:YAG, PC, FD, PS	500×10^{-6}	532×10^{-9}	3×10^{-12}	8.2×10^{3}	61×10^{-9}	90×10^{-12}	39×10^{-12}
Diode, discrete	1×10^{-6}	820×10^{-9}	60×10^{-12}	5×10^{3}	200×10^{-12}	10×10^{-12}	10×10^{-12}
Er fiber,[14] PML, FD	150×10^{-6}	780×10^{-9}	200×10^{-15}	5×10^{6}	30×10^{-12}	910×10^{-12}	360×10^{-12}
$Ti{:}Al_2O_3$, PS	1×10^{-3}	820×10^{-9}	100×10^{-15}	76×10^{3}	13×10^{-9}	1.7×10^{-9}	693×10^{-12}
Diode laser system[15]	2.3×10^{-3}	830×10^{-9}	$\approx 0.1t_s$ (tunable)	76×10^{6}	30×10^{-12}	98×10^{-12}	98×10^{-12}

$$V_m=\frac{q\mu_n n_\lambda r_0 dZ_0V_a}{2}\,\frac{t_R}{(t_R^2+t_L^2+t_S^2)^{1/2}}. \tag{9}$$

The maximum value of $n(t)$, n_m, also occurs at $t=0$ and is given by

$$n_m=n_\lambda r_0\frac{t_R}{(t_R^2+t_L^2)^{1/2}}. \tag{10}$$

Using n_m to substitute for the appropriate variables in Eq. (9) and then rearranging that result to solve for n_m in terms of V_m gives

$$n_m=\frac{2}{q\mu_n dZ_0}\,\frac{V_m}{V_a}\,\frac{(t_R^2+t_L^2+t_S^2)^{1/2}}{(t_R^2+t_L^2)^{1/2}}. \tag{11}$$

Equation (11) will be equated to a quantum-mechanical approximation for n_m,

$$n_m=\frac{\eta(1-R)}{L^2d}n_\lambda=\frac{\eta(1-R)}{L^2d}\,\frac{E_{p,m}}{E_p}=\frac{\eta(1-R)}{L^2d}\,\frac{E_{p,m}\lambda}{hc}, \tag{12}$$

to obtain an expression for $E_{p,m}$. Here η is the quantum efficiency and R is the reflectivity of the photoconductor ($\eta\approx1$ and $R\approx0.3$); n_λ is the number of photons impinging on the PC per optical pulse; E_λ is the photon energy; h is Planck's constant; c is the speed of light; and λ is the photon wavelength. Setting Eq. (11) equal to Eq. (12) and solving for $E_{p,m}$ gives

$$E_{p,m}=\frac{hcL^2}{\eta(1-R)q\mu_n}\,\frac{2}{Z_0}\,\frac{V_m}{V_a}\,\frac{(t_R^2+t_L^2+t_S^2)^{1/2}}{(t_R^2+t_L^2)^{1/2}}\,\frac{1}{\lambda}. \tag{13}$$

Note that the absorption depth does not appear in (13); however, the thickness of the LTG-GaAs layer relative to the photon absorption depth is important. If the epilayer is very thin, then Eqs. (12) and (13) must be multiplied by the quantity $1-\exp(-d_{epi}/d)$, where d_{epi} is the epilayer thickness. From Eq. (13) we can see that observation of a larger V_m requires larger optical pulse energies, as expected. Also from (13) we see the importance of the bandwidth of the oscilloscope relative to that of the optical pulses. (The bandwidth is inversely proportional to the FWHM, or t_S, for a Gaussian pulse.) The oscilloscope effectively acts to low-pass-filter the high-speed photoconductively generated electrical pulses, so that the shorter the duration of the optical pulse, for $t_L>T_R$, or the faster the photoconductor response, for $t_L<T_R$, the more pulse energy is required to observe a given V_m. If $t_L\gg t_S$, then $E_{p,m}$ becomes independent of the oscilloscope response. If $E_p\geq E_{p,m}$, then a signal having a peak magnitude of at least V_m on the oscilloscope can be observed.

3 Laser-System Comparison

A comparison of laser systems for short-electrical-pulse generation can be demonstrated by using Eq. (13), where $L=10^{-5}$ m and $\mu_n=350$ cm^2/(V s) for the PC-related variables, $Z_0=50\ \Omega$ for the oscilloscope impedance, the result is multiplied by 2 to compensate for losses in the optical path and any approximation errors, $t_R\ll t_L$, $V_m=0.2$ V, $V_a=10$ V, and $t_S=17.5$ ps or 7 ps for a 20-GHz or 50-GHz oscilloscope. The value for μ_n, 350 cm^2/(V s), is based on a comparison of measurements made on PCs using bulk semi-insulating (SI) GaAs and 160 °C LTG GaAs. Six laser systems are considered (see Table 1),[14,15] and their operational parameters were obtained either from the manufacturer or from the literature. The quantities $E_{p,m(17.5)}$ and $E_{p,m(7)}$ are the optical pulse energies required to observe the 0.2-V-peak-amplitude electrical pulse using a 17.5-ps and a 7-ps-rise-time oscilloscope. The last laser system considered provides pulse-width tuning, so that only one value for $E_{p,m}$ is given. In this case we will use $t_L\approx0.1t_s$ so that the laser pulse will not significantly affect the bandwidth of the photogenerated electrical pulse.

From Table 1, for the attenuated Nd:YAG system, we can see that there is not sufficient energy in the optical pulses to confidently generate the 0.2-V-peak-amplitude electrical pulses for the 20-GHz ($t_S=17.5$ ps) oscilloscope, but there is sufficient energy for the 50-GHz (t_S=7 ps) oscilloscope. However, the PCs may be redesigned or the power incident on the PC increased (to be discussed later) so that $E_{p,m(17.5)}$ approaches E_p. It is necessary to limit the laser power incident on the PC to avoid undesirable thermal effects. However, a pulse selector may also be used, which effectively reduces the average power incident on the PC without significantly affecting the peak optical power. This situation is shown for the second laser system listed, which is a pulse-selected, pulse-compressed, frequency-doubled Nd:YAG. For the discrete laser diode, there is sufficient energy in the optical pulses to easily generate the 0.2-V-peak-amplitude electrical pulses. However, the bandwidth associated with the diode's optical pulses is much less than that of the oscilloscopes. Consequently, the optical pulse width does not significantly affect $E_{p,m(17.5)}$ or $E_{p,m(7)}$, and the observed electrical pulse will resemble the optical pulse. The pulse-selected Ti:Al_2O_3 laser has sufficient energy per pulse to confidently generate 0.2-V electrical pulses for either oscilloscope. Moreover, the Ti:Al_2O_3 (typical average power of 1 W) can be attenuated and still provide sufficient optical pulse energy to generate 0.2-V electrical pulses, especially when the PC is redesigned or V_a increased. The diode laser system (resonator with amplifier and dispersion compensation[15]) will not provide sufficient energy per pulse to confidently generate 0.2-V electrical pulses. However, the PC may be redesigned so that $E_{p,m}$ comes closer to E_p. Fiber laser systems producing larger pulse energies[16] may also be employed, and using them in conjunction with PC modifications may allow the fiber laser to generate electrical pulses having the desired amplitude. However, the doubling efficiency (30%) that was used to calculate $E_{p,m}$ for the fiber laser referred to in Table 1 is very optimistic. For the nominally 100-fs pulses produced by the fiber lasers, the doubling efficiency of typical doubling crystals will be less than 10% because of the wide optical bandwidth.

If the PC gap width is decreased to 5 μm and V_a is decreased to 5 V (thereby maintaining the applied electric field of 1 V/μm), $E_{p,m}$ will be reduced by a factor of 2, thereby allowing lower-power laser systems to generate the 0.2-V-peak-amplitude electrical pulses. Furthermore, the applied electric field, 1 V/μm, used in calculating the values of $E_{p,m}$ is a conservative value for bulk semi-insulating GaAs PCs and can be easily increased. Moreover, for LTG GaAs PCs the field can be further increased because LTG GaAs has a higher breakdown voltage than semi-insulating GaAs.[4,17,18] Consequently, by reducing the PC gap width and increasing V_a, lower-power laser systems, such as the diode-resonator-compensator system, will also have adequate optical pulse energy to generate 0.2-V-peak-amplitude pulses.

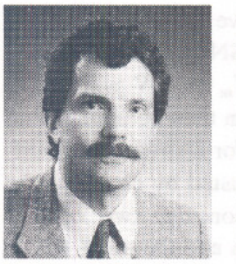
The effect of instrument thermal noise,

$$V_{n,\mathrm{thermal}} = 2(kTBZ_0)^{1/2}, \tag{14}$$

on $E_{p,m}$ should also be considered, where k is Boltzmann's constant, T is absolute temperature in kelvins, Z_0 is the magnitude of the impedance of the instrument, and B is the bandwidth of the instrument. For example, for T=300 K, Z_0=50 Ω, and B = 12.5 GHz, we have $V_{n,\mathrm{thermal}}=1\times10^{-4}$ V. The signal-to-noise ratio (SNR) of the measurement for $V_{n,\mathrm{thermal}}=1\times10^{-4}$ V and V_m=0.2 V is approximately 2×10^3, or 66 dB. The SNR can then be used to find a relative adjustment factor for $E_{p,m}$ for instruments of different bandwidths, where $E_{p,m}$ is adjusted by changing the target voltage V_m. For example, consider two oscilloscopes, one with a 50-GHz bandwidth and the other with a 12.5-GHz bandwidth. The thermal noise voltage for the 50-GHz oscilloscope is two times that of the 12.5-GHz oscilloscope. Therefore, if we wish to maintain the same SNR for observations made on the two oscilloscopes, V_m and, consequently, $E_{p,m}$ for the 50-GHz oscilloscope must be twice that for the 12.5-GHz oscilloscope.

References

1. D. Henderson, A. G. Roddie, and A. J. A. Smith, "Recent developments in the calibration of fast sampling oscilloscopes," *IEE Proc. A*, **139**, 254–260 (1992).
2. B. A. Bell, A. G. Perrey, and R. A. Sadler, "Gallium arsenide (GaAs)-based photoconductive switches for pulse generation and sampling applications in the nanosecond regime," *IEEE Trans. Instrum. Meas.* **IM-38**, 92–97 (1989).
3. D. H. Autson, "Picosecond optoelectronic switching and gating in silicon," *Appl. Phys. Lett.* **26**, 101–103 (1975).
4. F. J. Leonberger and P. F. Moulton, "High-speed InP optoelectronic switch," *Appl. Phys. Lett.* **35**, 712–714 (1979).
5. G. Mourou and W. Knox, "High-power switching with picosecond precision," *Appl. Phys. Lett.* **35**, 492–495 (1979).
6. D. H. Auston, A. M. Johnson, P. R. Smith, and J. C. Bean, "Picosecond optoelectronic detection, sampling, and correlation measurements in amorphous semiconductors," *Appl. Phys. Lett.* **37**, 371–373 (1980).
7. R. B. Hammond, N. G. Paulter, A. E. Iverson, and R. C. Smith, "Sub-100 ps bulk-recombination-limited InP:Fe photoconductive detector," in *IEEE Int. Electron Devices Meet. Tech. Dig.*, pp. 157–160 (1981).
8. P. R. Smith, D. H. Autson, A. M. Johnson, and W. M. Augustyniak, "Picosecond photoconductivity in radiation-damaged silicon-on-sapphire films," *Appl. Phys. Lett.* **38**, 47–50 (1981).
9. R. E. Matick, *Transmission Lines for Digital and Communication Networks*, McGraw-Hill, New York (1969).
10. F. W. Smith, A. R. Calawa, C. L. Chen, M. J. Manfra, and L. J. Mahoney, "New MBE buffer used to eliminate backgating in GaAs MESFET's," *IEEE Electron Device Lett.* **EDL-9**, 77–80 (1988).
11. S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed., Wiley, New York (1981).
12. W. Feller, *An Introduction to Probability Theory and Its Applications*, Vol. II, 2nd ed., Wiley, New York (1971).
13. S. Gupta, M. Y. Frankel, J. A. Valdmanis, J. F. Whitaker, G. A. Mourou, F. W. Smith, and A. R. Calawa, "Subpicosecond carrier lifetime in GaAs grown by molecular beam epitaxy at low temperatures," *Appl. Phys. Lett.* **59**, 3276–3278 (1991).
14. M. E. Fermann, M. J. Andrejco, Y. Silberberg, and A. M. Weiner, "Generation of pulses shorter than 200 fs from a passively mode-locked Er fiber laser," *Opt. Lett.*, pp. 48–50 (1993).
15. P. J. Delfyett, L. Florez, N. Stoffel, T. Gmitter, and N. Andreadakis, "200-fs optical pulse generation and intracavity pulse evolution in a hybrid mode-locked semiconductor diode-laser/amplifier system," *Opt. Lett.*, pp. 670–672 (1992).
16. G. Lenz, K. Tamura, H. A. Haus, and E. P. Ippen, "All-solid-state Femtosecond Source at 1.55 μm," *Opt. Lett.*, pp. 1289–1291 (1995).
17. M. Kaminska, Z. Liliental-Weber, E. R. Weber, T. George, J. B. Kortright, F. W. Smith, B.-Y. Tsaur, and A. R. Calawa, "Structural properties of As-rich GaAs grown by molecular beam epitaxy at low temperatures," *Appl. Phys. Lett.* **54**, 1881–1883 (1989).
18. M. Kaminska, E. R. Weber, Z. Liliental-Weber, R. Leon, and Z. U. Rek, "Stoichiometry-related defects in GaAs grown by molecular beam epitaxy at low temperatures," *J. Vac. Sci. Technol.* **B7**, 710–713 (1989).



Nicholas G. Paulter received the MS degree in chemistry from the University of New Mexico in 1988 and in electrical engineering from the University of Colorado in 1990. He was with Los Alamos National Laboratory, Los Alamos, NM, from 1980 to 1989 and was involved in the study of fast electrical phenomena and in the development of high-speed photoconductors for use as ultrafast light detectors and sampling gates. In 1989 he joined the National Institute of Standards and Technology (NIST), Boulder, CO, to develop transient pulse measurement techniques and analysis. He is presently with NIST in Gaithersburg, MD. His present research interests include semiconductor physics, electro-optics, ultrafast electronic phenomena, and waveform/data processing and analysis.