A time resolved intense pulsed light spectral analysis system

D. M. Clarkson · D. Gill · M. Odeke

Abstract Intense pulsed light systems are currently in widespread use in clinical applications. Verification of spectral content and associated pulse waveforms is, however, not featured in product support and calibration. A measurement system was developed to determine the spectral output of such sources within a series of discrete wavelength intervals. Such a system utilised a series of 11 broadband optical filters with centre wavelengths within the range 450–950 nm in circuit with silicon photodiodes as optical detectors. Signals were captured using a low cost 8-channel 16-bit universal serial bus data capture module interfaced to a laptop computer. This allowed the pulse profile of selected filter components to be separately captured and analysed. Calibration of individual filter channels was undertaken using a Bentham dmc150 spectroradiometer and reference tungsten light source. Initial measurements undertaken of the intense pulsed light output of a Lumenis One system using the system are described.

Keywords Intense pulsed light · IPL · Spectrophotometry

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Introduction

Intense pulsed light (IPL) systems are currently widely used in clinical/cosmetic applications [1–5]. There is generally a lack of information about the output spectral radiation of IPL sources [6], although pulse profile information can provide useful information about system performance [7]. From a measurement perspective, this element of uncertainty is unsatisfactory in terms of possible verification of device output. From a viewpoint of clinical application of such technology, this can give rise to corresponding uncertainty about the output parameters being applied for patient treatments and can make comparison of systems difficult.

The output measurement of laser systems is simplified by the utilisation of discrete well-identified wavelengths. For IPL sources, a detailed description of the output optical radiation would consist of a time sequence of irradiance values at discrete wavelength intervals and sampled over the time period of the emitted pulse—usually in excess of 3 ms. To thus fully characterise a typical IPL system at 1-nm wavelength intervals would require 601 channels between 500 and 1,100 nm with each channel sampled at a rate of around 10 kHz. Routine measurement of such parameters by affordable equipment systems is impracticable.

There are also some basic issues about the light output of such systems that require clarification. It is not clear, for example, if the pulse characteristics of discrete wavelength contributions behave in an identical manner or if the interactions of drive effects within the flashtubes render irradiance at specific wavelengths a more complex function of time. There are also more basic questions such as changes to output spectra with tube and filter ageing and changes to output spectra as a function of radiant exposure setting with a given IPL filter. A simplified measurement

system was developed using a series of 11 wavelength intervals to investigate such effects. Initially, observations were made on the intense pulse light output of a Luminous One® system (Lumenis, Santa Clara, CA).

Table 1 indicates the typical range of relative detected signal for variation of pulse duration and radiant exposure over indicated ranges. This indicates that at a specific distance and for a specific filter output, a detected signal may vary by a factor of 100, as basic output parameters of radiant exposure and pulse duration are altered. There may also be effects where the output spectrum is distributed across a broad or narrow range of wavelengths. One of the key design parameters of the detection system is to select channel gains to cope with the potential wide dynamic range of IPL sources.

Materials and methods

Detection circuit and filter assembly

The detection channels consisted of half-inch-diameter band-pass optical filters (Davin Optronics, Watford, UK) with light detection using silicon photodiodes (Centronic, Croydon, UK). Channels 1–4 utilised photodiodes of a 5.0-mm^2 area, and channels 5–16 utilised photodiodes of a 1.0-mm^2 area. The use of larger area photodiodes was designed to increase channel sensitivity at shorter wavelengths where the photodiode sensitivity is reduced. Initially, only channels 1–11 were populated with broadband optical filters. Fused silica glass Vitrosil ® windows (UQG, Cambridge, UK) were used to protect filter surfaces from ingress of contamination. The set of filters was housed in a block of aluminium with centres of photodiodes 1.8 cm apart. The blocking range of the filters was within the range 300–1,200 nm.

The basic photodiode detection circuit using a photovoltaic mode without reverse biasing as applied to 16 channels is indicated in Fig. 1. The circuit design also included four DG409 analogue multiplexers to allow selection of four channels from channels 5–12 under software control as indicated schematically in Fig. 2. This allowed the software to sample from up to 12 channels. The operational amplifiers (LM214) would saturate at an output voltage of around 3.6 V.

Calibration of unit

The optical transmission characteristics of the optical channels were verified using a Bentham dmc150 spectroradiometer using a CL6 tungsten light source (Bentham Instruments, Reading, UK). A DH-30 photomultiplier detector was used in the wavelength range 350–849 nm for channels 1–8 and a DH-Si silicon detector with reduced sensitivity in range 800–1,100 nm for channels 9–11. Measurements of filter transmission characteristics were made at 1-nm intervals in the plane of photodiode detection at A as indicated in Fig. 3 with the components of glass cover and bandpass filter present and then absent. Light from a miniature integrating sphere with a 7-mm-diameter input aperture was connected to the dmc150 spectroradiometer by means of a 2-m optical fibre. These measurements confirmed the effective optical bandwidth characteristics of the filter channels as FWHM (full width half maximum) values.

The CL6 reference light source has a reference output irradiance with traceability to national standards as indicated in Fig. 4. Calibration of the detector array was undertaken with reference to the defined measurement plane of the reference light source at 0.8 cm from the exit plane of the external lamp housing. Values of channel voltage were recorded with this reference plane of illumination co-incident with the front face of each of detection channel and the value of gain resistance VR$_n$ set to 100 kΩ. The input irradiance of each channel was derived from the effective channel bandwidth (FWHM value) and the known output irradiance of the CL6 reference light source as a function of wavelength. Values of sensitivity for each of the measurement channels were initially referenced as irradiance in mW/m^2 over the effective bandwidth of the specific filter per volt of detected channel voltage. Initial measurements of IPL output were made at around a distance of 50 cm from the applicator surface and with use of an IPL applicator with a 1-cm^2 surface area.

Data capture and analysis

Channel voltages were captured using a low cost 8-channel, 16-bit universal serial bus (USB) analogue I/O module USB1608FS (Measurement Computing, Middleboro, MA), with maximum single analogue channel throughput rate of

Table 1 Indication of relative detected signal from photodiode detectors within range of 5–50 ms of pulse duration and 5–50 J/cm^2 for output radiant exposure

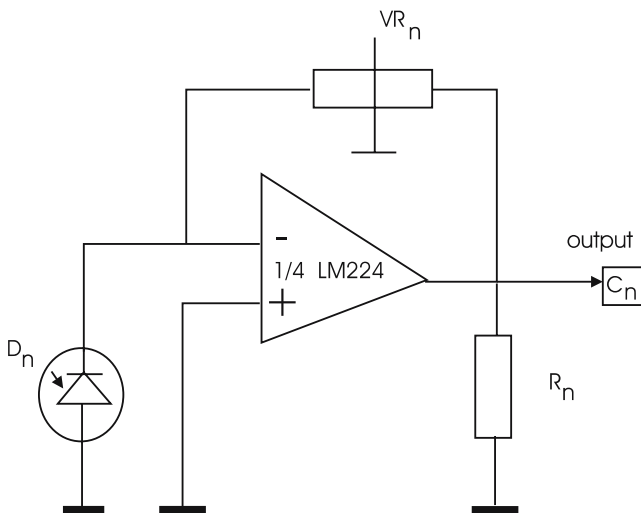|	5 ms	10 ms	20 ms	50 ms
5 J/cm^2	10.0	5.0	2.5	1.0
10 J/cm^2	20.0	10.0	5.0	2.0
20 J/cm^2	40.0	20.0	10.0	4.0
50 J/cm^2	100.0	50.0	25.0	10.0

Fig. 1 Basic detection circuit using operational amplifier in photo-voltaic mode. Initially VR_n was set at 100 kΩ for calibration and to 5 kΩ for routine measurements
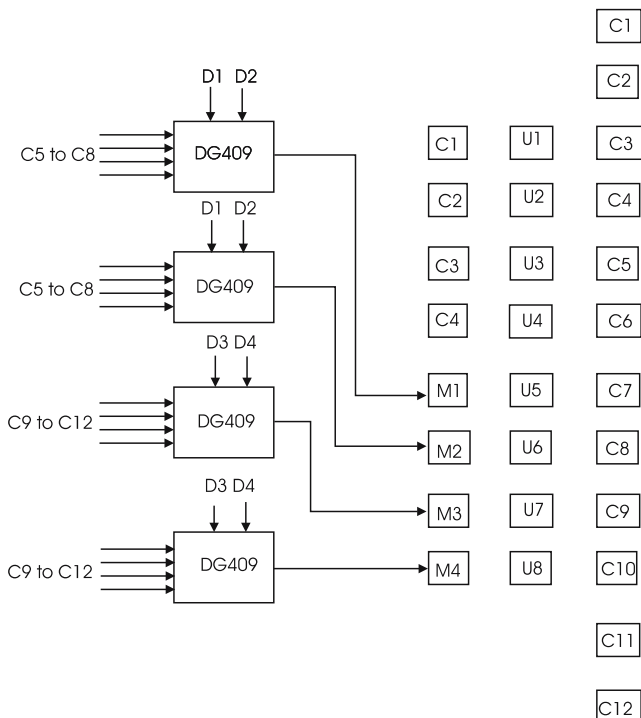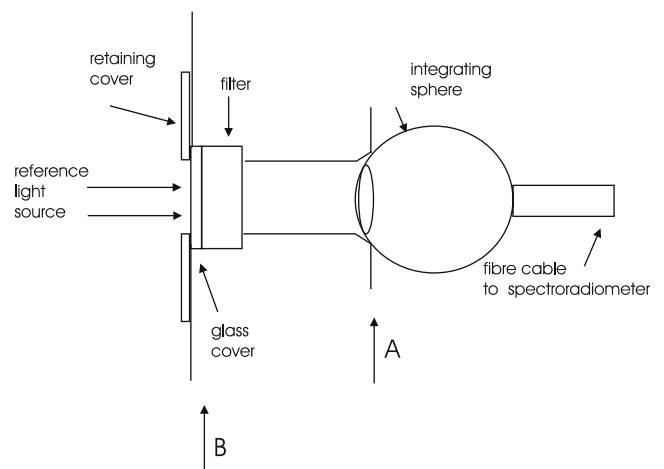
Fig. 3 Filter housing showing method of verification of light transmission characteristics of each channel. The reference plane for calibration coincides with the incident plane of glass filter covers, indicated as *B*. *Plane A* indicates plane of photodiode detection

50 kHz and corresponding 8-channel capture rate of 10 kHz. In addition, eight programmable digital input/output lines were also available. Signals were captured using a Dell Inspiron laptop computer (Dell, Round Rock, TX). Power for the detection circuit was supplied directly from the +5-V supply of the USB module. Data capture could be activated automatically at run time or by means of an external trigger signal using channel 16 with no optical filter present. The data capture software DAS-WIZARD® was initially used to export data directly to Excel® at maximum data rates of the hardware system without the use of analogue multiplexer devices. The captured data were subsequently displayed/processed using MatLab® and Excel®.
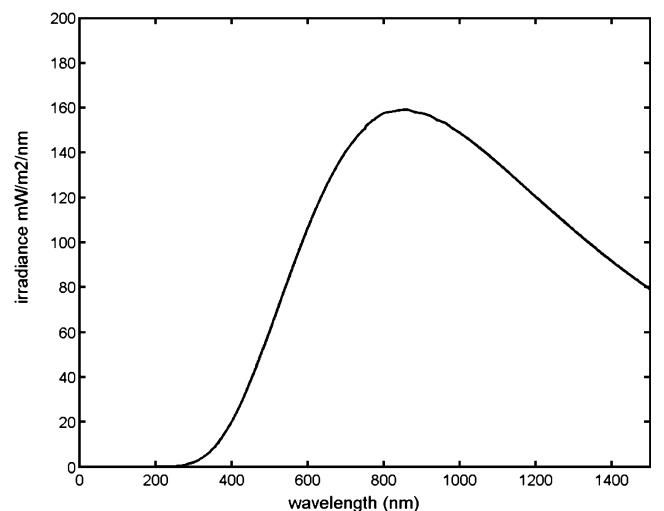
Fig. 2 Schematic of signal derivation and connection. On the *right* is shown the layout of three separate terminal block units (C1 to C12, U1to U8 and C1to M4) to facilitate connection of signals to the USB interface. On the *left side* is shown how signals M1 to M4 can be selected from direct channel values C5 to C12 with selection of digital control lines D1, D2, D3 and D4. On the *right*, row U1 to U8 indicates the terminal block with direct connection to the analogue input channels of the USB interface. In addition, row C1 to C12 indicates the terminal block with direct channel connection to the photodiode detection channels

Fig. 4 Reference irradiance of calibration light source—equivalent to 6,334 lux
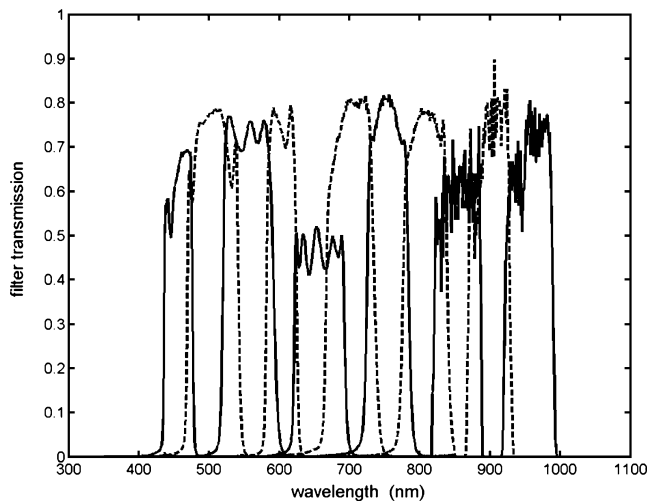
Fig. 5 Transmission characteristics of series of optical channels indicating fraction of light transmitted. Channels 1 to 8 were determined using a photomultiplier detector while set 9 to 11 were measured using a silicon photodiode detector

Results

Filter characteristics and channel sensitivities

The optical transmission characteristics of the various channels as determined using the measurement configuration of Fig. 2 are shown in Fig. 5. Summary parameters are also listed in Table 2. The filters provide continuous detection within the intended limits of spectral measurement with some degree of overlap between channels. There is also some degree of variation of transmission within the FWHM interval of each filter. The channel with centre wavelength 650 nm appeared to have a reduced transmission compared with the manufacturer supplied specification. Table 3 also indicates the nominal channel sensitivities derived using the CL6 calibration light source and with 100-kΩ values of gain resistance VR_n. Measurements of the output spectra of IPL sources were subsequently made with resistance values of

VR_n set close to 5 kΩ. Channels 6–11 demonstrate essentially similar sensitivity values. The use of larger area photodiodes for channels 1–4 to achieve higher channel sensitivity would not appear essential. The high values of peak power associated with IPL output, however, require care to prevent saturation of photodiode detectors. The dynamic range of the measurement system would have been further improved by reducing the values of VR_n to around 1 kΩ or less.

Preliminary measurements

Figure 6 indicates a typical measurement sequence of a 10-ms pulse with a 515-nm filter employed and channels 1–11 displayed. Data for channels 9, 10 and 11 were obtained by manual switching of data on the terminal block. Output values indicate the effective irradiance value per nanometre within the FWHM of each filter in units of mW m^{-2} nm^{-1}. Figure 7 displays the data as integrated radiant exposure within the FWHM of each filter per nanometre in units of J m^{-2} nm^{-1}. The angle of incidence of light at filters is designed to be as small as possible to reduce any effect of change in wavelength response of optical filters.

Discussion

Measurement system

The development was undertaken using readily available filter components and low cost computer interfaces. The described system demonstrates the ability to provide cost-effective test equipment to verify the basic output parameters of IPL sources as defined within broadband filter ranges. It is essentially practical to determine spectral profiles based on bandpass filters of a FWHM value between 400 and 1,100 nm. A key consideration, however,

Table 2 Details of optical characteristics of the filter set used together with corresponding intrinsic sensitivity of silicon photodiode material at the centre wavelength of the filter

FWHM bandwidth (nm)	Centre (nm)	Diode no.	Transmission within FWHM (%)	Silicon sensitivity (A/W)
40	457	1	61.5	0.16
72	506	2	69.6	0.28
72	557	3	66.7	0.36
44	603	4	68.9	0.40
72	658	5	45.1	0.44
68	701	6	70.5	0.47
58	755	7	72.5	0.51
64	808	8	71.1	0.53
70	850	9	55.5	0.54
60	900	10	68.7	0.53
65	950	11	64.7	0.48

Table 3 Details of filter set used and associated derived channel sensitivity

Diode no.	Calibration voltage for 100 kΩ resistor value	Calibration irradiance Within FWHM (mW/m^2) of CL6 light source	Channel sensitivity mW/m^2 at 1-V output within FWHM (VR$_n$=100 kΩ)
1	0.151	1,662	11,007
2	0.579	4,577	7,905
3	1.121	6,287	5,494
4	0.774	4,737	6,120
5	0.217	9,325	42,972
6	0.347	9,548	27,515
7	0.378	8,797	23,272
8	0.374	10,086	26,968
9	0.395	10,633	26,918
10	0.402	9,606	23,895
11	0.389	11,034	28,365

of such a system relates to effective calibration of the measurement system. The CL6 calibration light source provides a convenient well-defined reference spectrum that facilitates the calibration process, although the relatively low irradiance levels require calibration at one level of VR$_n$ and the active measurements to be made at another lower value. For channels 1–3, however, the calibration irradiance rises rapidly with wavelength so that levels are rapidly changing within these filter intervals—which could increase measurement uncertainty.

In terms of system sensitivity, the factors influencing the detected signal included output radiant exposure, pulse duration, pulse sequence (single, double and triple), gain of USB1608FS module, distance from detector array, area of radiating IPL surface and spectral content of the light output. This can give rise to a significant dynamic range of

the IPL outputs, which has to be accommodated within measurement configuration and technique.

The 8-channel data capture rate of 10 kHz is essentially adequate for observing variations within pulse profiles of a given bandpass filter, although higher data rates may be required for differentiating rise and fall time edges within different wavelength bands. For measurement convenience, a 16-channel capture system is in development, which will also have the potential to measure into the ultraviolet range of output spectra.

Output measurements

Some basic features of light output were identified within the pulse characteristics of a specific IPL output system to demonstrate the measurement potential of such a system.
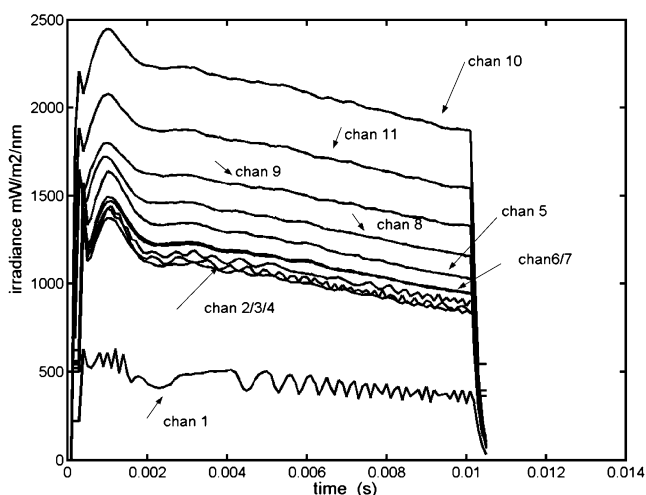

Fig. 6 Output pulse Lumenis One system, 10-ms pulse at 10-J/cm^2 radiant exposure, 10-kHz sampling with 515-nm filter indicating irradiance per nanometre
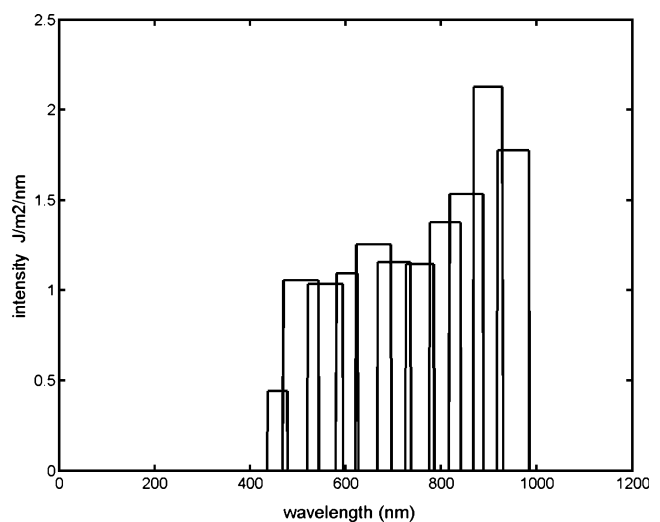

Fig. 7 Output pulse Lumenis One system, 10-ms pulse at 10-J/cm^2 radiant exposure, 10-kHz sampling with 515-nm filter indicating integrated energy per nanometre within bandpass filters

Initial observations indicate that for the specific IPL system investigated, the pulse durations are in accord with set parameters and that essentially separate wavelength contributions demonstrate the same time-varying function. While estimations were made of spectral output within specific wavelength bands, these could not readily be compared with defined output specifications.

Work is currently on going to investigate a subset of commonly used IPL systems to review the range of associated performance specifications with actual measured performance.

Development of measurement systems as described, however, allows verification of pulse output of IPL systems and makes possible the definition of output parameters of such systems for routine verification. While existing guidelines for safety evaluation exist [8, 9], work is ongoing to develop more focused product standards for both IPL output specifications and corresponding eyewear [10]. The development of practical and effective standards requires the development of correspondingly practical and effective means of verifying performance. In addition, such described measurement components for determining IPL output have the potential to be an integral component of IPL systems—to potentially provide a means of monitoring IPL performance as a result of IPL flashlamp and filter degradation.

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