ORIGINAL ARTICLE

Verification of switched liquid crystal eye protection filters

D. McG. Clarkson · C. Swift

Abstract Protective eye-wear which utilizes switched liquid crystal can provide protection for operators using intense pulsed light sources (IPLs). Such eye protection devices combine the properties of useful visual transmittance in the nonactivated state and low light transmission in the active blocking state. The performance of a specific LightSpeed device has been determined using a series of bandpass optical filters coupled to photodiode detectors with signals being captured using a USB interface. Such measurements have allowed key switching parameters of these devices to be determined as part of the process of assessing their effectiveness. Measurements of optical density of transmitting state and blocking state were also determined using a double grating spectroradiometer. A simple model of active filter function was developed and applied to specific IPL pulse profiles.

Keywords Intense pulsed light · IPL · Spectrophotometry · Eye protection

Introduction

Intense pulsed light sources (IPLs) are potentially a significant optical hazard for both operators of such

equipment and patients receiving treatment. For the patient, acceptable levels of eye protection can readily be achieved by the use of totally 'blocking' eye-wear. For the operator, however, the conventional approach is to achieve a compromise between visual transmittance and ocular protection [1]. The key hazard identified is the retinal thermal hazard [2, 3] where each light flash of the IPL has the potential to thermally damage retinal structures.

While light-switched filters for welding applications have been available for some time, it is only recently that equivalent technology has been available as a means of eye protection for operators of IPLs. The IPL output of a Lumenis One system was used to verify the performance of a LightSpeed light-switched filter (Glendale, Smithfield, RI). The generic technology employed by such active filters is that detection of a light pulse by a photodetector establishes a voltage across a liquid crystal film which causes it to change optical density.

Materials and methods

Detection circuit and filter assembly

A measurement system previously developed for characterizing the output spectra and pulse profile of IPLs [4, 5] was used for the determination of the filter characteristics of the LightSpeed unit. This comprised an array of 15 photodiode detection channels with centre band wavelengths in the range 405 nm to 1107 nm.

Response measurement

Figure 1 indicates schematically the use of specific channels 1 and 4 where channel 1 (centre wavelength

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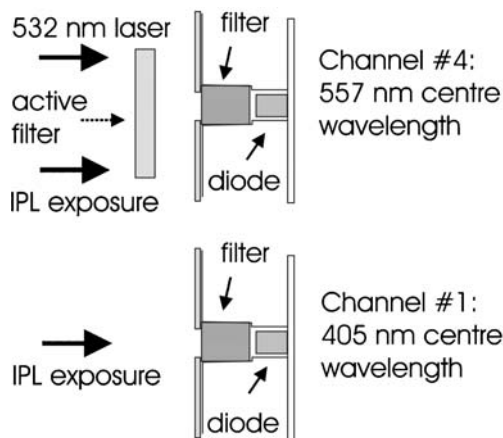
Fig. 1 Measurement configuration with channel 4 (centre wavelength 557 nm) detecting 532-nm laser diode signal transmitted through LightSpeed filter and channel 1 (centre wavelength 405 nm) directly detecting IPL exposure

405 nm, half-power bandwidth 43 nm) is only exposed to the IPL output and channel 4 (centre wavelength 557 nm, half-power bandwidth 72 nm) is exposed to both the IPL output and a class 2 532-nm laser. The gain settings on the detector channels were set at levels around 1,000 times higher than used with normal detection modes with IPL signals.

Data were captured using a 16-channel 16-bit USB analogue input module USB1616FS (Measurement Computing, Middleboro, MA). The maximum data capture rate for channels 1 and 4 was 25 kHz and that of a single channel 50 kHz. The data capture software DAS-WIZ-ARD was initially used to export data directly to Excel. Captured data were subsequently displayed/processed using MatLab.

The Lumenis One IPL module utilizes output filters in the range 515 nm to 755 nm. Output pulses could also be configured on the basis of pulse width, delay between pulses and number of pulses in the output train. In addition, the size of surface applicator could be selected from either 1 cm^2 or 5 cm^2. For some measurements of direct IPL output, it was necessary to reduce light output of the IPL in order not to saturate the detector channel. This was achieved, for example, by selection of channel 1 (centre bandwidth 405 nm) with a 755-nm filter and a small 1-cm^2 applicator head.

Optical density measurement

The steady-state values of optical density (transmission and blocking) of the LightSpeed unit were also determined in the range 250 nm to 849 nm using a Bentham dmc150 spectroradiometer (Bentham Instruments, Reading, UK).

Using a reference lamp (Bentham type CL6-H), spectra were recorded without the active filter present and then with the active filter present in transmission mode and blocking made. Rapid movement of a hand-held fibre light source across the light sensor maintained the LightSpeed unit in a blocked state.

Pulse energy transmission measurement

The percentage transmission through the LightSpeed unit was measured over the range 5 ms to 50 ms at a set output fluence level of 10 J/cm^2 for the 515 nm filter on the Lumenis One IPL and with the large 5-cm^2 applicator selected. Specific measurements were recorded on 3A-P and 30(150) heads of an Ophir Nova system (Ophir Optronics, Jerusalem, Israel)). A fixed distance was maintained from the LightSpeed unit in order not to damage exposed surfaces.

Results

Single-channel observations with active filter and 532-nm laser

Figure 2 shows the 532-nm laser diode signal as detected by channel 4 (centre wavelength 557 nm) with the separate phases pre-IPL pulse transmission mode, IPL pulse exposure, subsequent blocking mode of the active filter, and recovery of active filter to transmission mode about 0.5 s after initial IPL pulse detection.
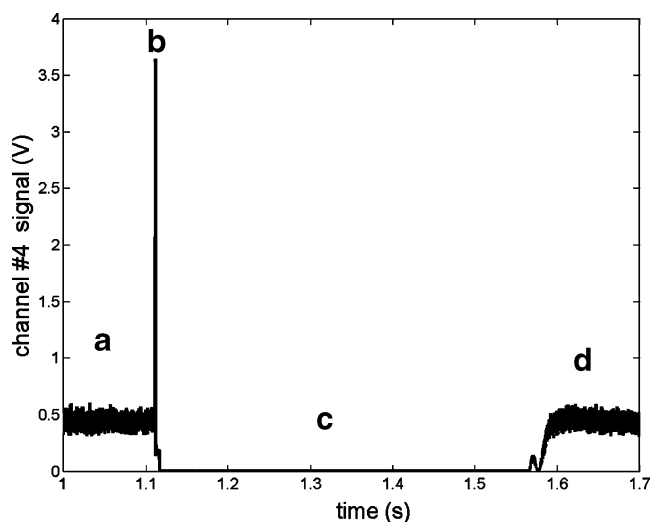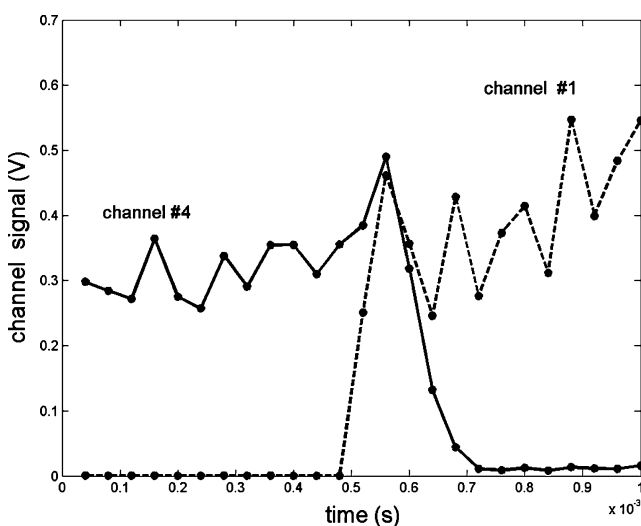

Fig. 2 Output channel 4 showing detection of the 532-nm laser (A), initial detection of IPL pulse (B) followed by the blocking mode interval (C) and recovery to transmission mode (D)

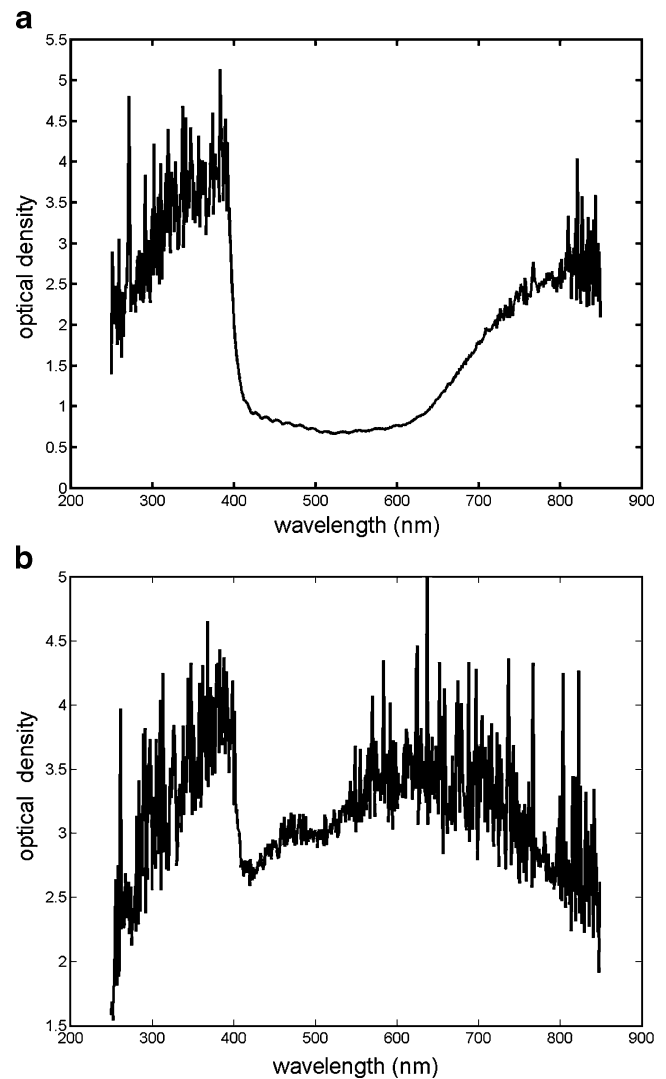Dual channel observations using 532-nm laser diode

Using the measurement configuration of Fig. 1, channel 4 was again monitored with the 532-nm laser diode transmitted through the LightSpeed unit and with channel 1 (centre wavelength 405 nm) open to detect direct IPL output. In this configuration the 755-nm filter of the Lumenis One was used and with the smaller 1 cm^2 area applicator in place. The distance between the applicator and the detector assembly was around 1 m. This was to minimize the detected level of the IPL by channel 4 to prevent signal saturation. Figure 3 indicates the loss of transmitted signal of the 532-nm laser in channel 4 with the start of detection of the IPL pulse in channel 1. This indicates that the level of the 532-nm signal was reduced significantly within 0.25 ms of the onset of the IPL pulse.

Steady-state transmission values

Figure 4a shows the variation in optical density within the wavelength range 250 nm to 849 nm, indicating typically values around 0.6 in transmission mode within the wavelength range 400 nm to 700 nm. Comparable values of optical density in the blocking mode are shown in Fig. 4b, indicating a value of around 2.5 within the range 400 nm to 700 nm. The IPL eyewear was shown to be providing permanent blocking of optical density greater than 2.5 at wavelengths less than 400 nm and greater than 800 nm. This generally agrees with the manufacturer's product information. The large variation in optical density was probably caused by the relatively low level illumination source used.

Fig. 4 **a** Optical density values derived during the transmission mode, indicating relatively high optical density for wavelengths less than 400 nm and greater than 700 nm. **b** Optical density values derived during the blocking mode show an increase in optical density between 400 nm and 700 nm

Pulse energy transmission measurements

The percentage transmission was consistently recorded at around 0.05% over the range of pulse durations specified. This invariance of transmission was anticipated from the speed of response of the LightSpeed eyewear and is further discussed below.

Discussion

Active measurements

The response performance of active switching was within around 0.25 ms. Observations were made at normal

Fig. 3 Recording of separate effects of loss of transmission of channel 4 (532-nm diode) and start of detection of IPL output of channel 1 (sampling rate 25 kHz)

incidence. The state of polarization of the incident light was not verified, although IPL systems are not expected to have any significant polarization present. Also, variation in transmission states as a function of angle of incidence was not determined.

General observations

With low levels of light transmission in the blocking mode, it is likely that there is a component of the light passing into the pupil during direct exposure resulting from light scatter around the periphery of the eye-wear where it contacts the face of the operator.

With failure of the battery supply, the unit will fail in the transmission state rather than the blocking mode. This is the opposite of the required fail-safe function of the unit. In transmission mode, however, wavelengths less than 400 nm and in excess of 800 nm are effectively blocked and with around 20% maximum transmission in the range 400 nm to 800 nm.

Basic model of active filter response

The time-varying transmission across a defined wavelength range can be expressed as:

$$Tr(t) = TRa.e^{-t/t1} \, TRb.\left(1 - e^{-t/t2}\right) \qquad (1)$$

where Tr(t) is the effective transmission at time t after the start of the IPL pulse, TRa is the steady-state transmission in transmission mode, TRb is the steady-state transmission in blocking mode and t1 and t2 are relevant time constants. It is assumed that the optical transition is coincident with the start of the IPL pulse. The dominant term is TRa which
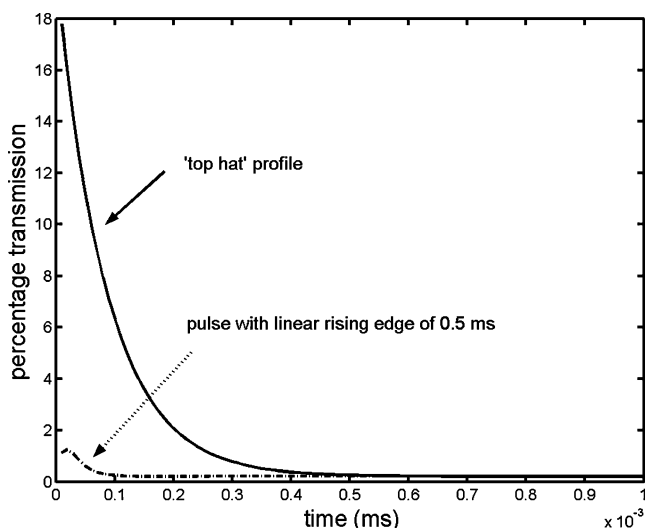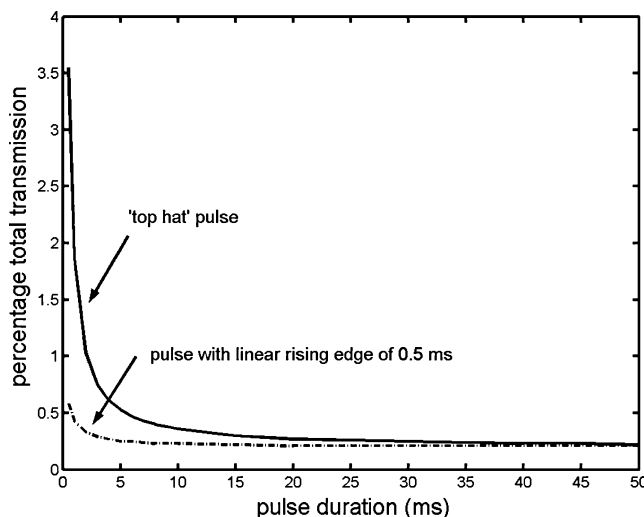

Fig. 6 Estimated percentage total transmission of LightSpeed eye-wear for a 'top hat' pulse and an equivalent pulse with a linear leading rising pulse of 0.5 ms width

replicates the initial rapid fall of transmission value. The term TRb confirms the blocking level of transmission.

Based on observations of actual IPL output waveforms, there will be a variation in the speed of switch-on of the IPL pulse. Figure 5 indicates the effect of a simulated 10-ms pulse with instantaneous switch-on ('top hat') compared with a pulse with a linear rising edge of 0.5 ms. For the more rapidly switching pulse, a larger fraction of the incident light is transmitted compared with the more slowly switching pulse.

Figure 6 indicates predicted total energy transmission percentage values as a function of pulse duration for a 'top hat' pulse and one with a linear rising edge of 0.5 ms. The values of TRa, TRb, t1 and t2 used in Eq. 1 were 0.2, 0.002, 0.000085 and 0.000085, respectively. The transmis-

Fig. 5 Initial transmission curves for a 'top hat' IPL pulse and a pulse with a linear rising edge of 0.5 ms. The 'top hat' pulse has significantly higher transmission initially
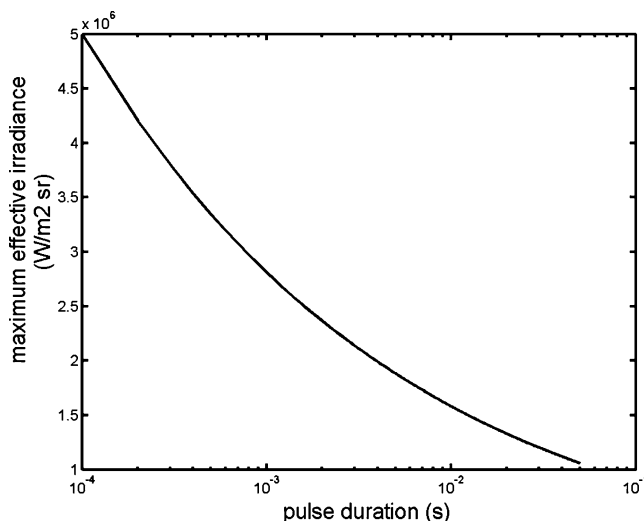

Fig. 7 Estimated variation of maximum permissible L_{RTH} as a function of pulse duration

sion level tended towards the limit of the blocking level with increased pulse duration. Levels of transmission rose significantly for pulse durations shorter than about 1 ms.

Figure 5 also indicates that the effective pulse duration of the light transmitted to the eye is significantly reduced, although this is influenced significantly by the rising edge of the IPL pulse. This 'shortening' of the IPL pulse will in turn alter safety assessment calculations. For the pulse duration range 18 μs to 10 s, the maximum permissible effective radiance L_{RTH} can be calculated from the equation [2]:

$$L_{RTH} = \frac{5 \times 10^4}{C_\alpha t^{0.25}} W/m^2.sr \qquad (2)$$

where t is the pulse duration and C_α is a correction factor based on the angle subtense of the system. Assuming a value of C_α of 0.1, Fig. 7 indicates the variation of L_{RTH} with pulse duration. This indicates that for an initial 'top hat' output pulse of 10 ms which is transformed to an effective pulse width of around 0.1 ms (Fig. 5), the maximum permissible exposure is increased by around a factor of 3. This represents the minimum level of attenuation that the active filter will provide. For IPL pulses which have finite rise times, the active filter will, in addition, attenuate transmitted light more significantly.

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