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Design and performance characteristics of an electromagnetic interference shielded enclosure for high voltage Pockels cell switching system

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Abstract. An electro-magnetic interference noise shielding enclosure for Pockels cells for high speed synchronized switching has been set-up and tested. The shielding effectiveness of the aluminum enclosures housing the Pockels cells and the electronic circuitry has been measured using a high impedance probe and is found to be ~ 50 dB. This ensures a noise-free and synchronized electro-optic switching in an Nd:glass re-generative amplifier of chirped pulse amplification based table top terawatt laser system.

Keywords. EMI shielding; regenerative amplifier; Pockels cell.

1. Introduction

The polarization rotation of a pulsed laser beam over a given temporal duration is required in many scientific and technological applications like extraction of a single pulse from a laser pulse train (Kong *et al* 1997), reduction of amplified spontaneous emission (ASE) component from laser pulses from a laser chain (Yamakawa *et al* 1991), development of pulse duration tunable oscillator in range sub ns to few ns (Sharma *et al* 2005 & 2007), temporal slicing of a laser pulse (Chakera *et al* 1996), etc. This may be accomplished using synchronized operation of electro-optic switches (Pockels cell) energized by suitable high voltage pulse. The Pockels cells are also routinely used in Q-switched and cavity dumped lasers (Charlton & Ewart 1984, Houtman *et al* 1982), re-generative amplifiers (Sharma *et al* 2005), etc. A re-generative amplifier for a chirped pulse amplification (Strickland & Mourou 1985) based ultra-short ultra-high power laser system (Aoyama *et al* 2003) may involve a single pulse selection after pulse stretcher from a laser pulse train generated by a CW mode locked femtosecond laser oscillator, its injection into the amplifier cavity, and its ejection from the amplifier cavity after sufficient amplification. Thus its operation also requires synchronized switching of two or more Pockels cells with an accuracy of the order of a nanosecond. Next,

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a re-generative (regen) amplifier is mostly followed by a pulse cleaner unit, which also uses a Pockels cell, to discard any pre-pulses and ASE of the main laser pulse from the regen amplifier cavity.

For the above stated applications and several others (Rai *et al* 1999), switching of very high voltage with a rise time of the order of a nanosecond is required. In the case of regenerative amplifier (Sharma *et al* 2005), the pulse selection, injection, and ejection are usually done using KD*P based Pockels cells as electro-optic switches, which require switching of high voltage (3·6 kV) electrical pulses in a short time of ~ 1 ns. The fast switching of such high voltages generates electro-magnetic interference (EMI) noise. The electric field dominated EMI noise thus generated normally contains a large radiative component, which may be picked up by electronic circuits kept in the vicinity. This may, in turn, distort the electrical trigger signals to various units resulting in their spurious triggering. In the case of sequential switching of Pockels cells (as required in a regen amplifier), the EMI noise radiated out during switching of one Pockels cell may generate a spurious trigger signal for subsequent switching of another Pockels cell, thereby disturbing the timing control of the sequential switching. Further, the firing of flash lamps (which are normally fired in advance so that peak population inversion is generated in the laser rod at the time of switching of the Pockels cell) may also generate spurious triggering of various Pockels cells in the laser system. In addition, EMI noise may adversely affect the performance of nearby placed electronic circuits. For example, detection of laser pulses (Becker *et al* 1994) using photodiode-oscilloscope combination. Therefore, in order to have precise, synchronized switching of different Pockels cells and proper operation of the related electronic circuits, one necessarily requires EMI noise shielding of Pockels cells and study of electro-magnetic compatibility (EMC) of the electronic circuits.

In principle, EMI shielding may be achieved by placing the complete switching unit (high voltage switching circuitry and Pockels cell) inside a metal enclosure with suitable holes for various cables (trigger, power supply, etc.) and laser beam entrance and exit. The principle and techniques of EMI noise shielding have been well documented in literature (Thomas *et al* 2001, Olyslaser *et al* 1999, Mardiguian 1992). However, one does not find a detailed report on EMI shielding of Pockels cells and their EMC for application in a re-generative amplifier requiring synchronized switching of two or more Pockels cells. The shielding effectiveness (SE) value of an EMI shielded enclosure is adversely affected by the presence of various apertures, their number and locations, which are different for different experimental conditions. It is therefore desirable to design, fabricate and study the performance of simple, low cost EMI shielded enclosures to provide shielding to various electro-optics units of a laser system. In this paper, we present experimental results on shielding effectiveness of an aluminum enclosure set-up for EMI shielding of different Pockels cells in a Nd:glass re-generative amplifier of our chirped pulse amplification based table top terawatt laser systems and study of its electromagnetic compatibility (EMC) with electronic circuits used for high voltage fast switching and detection of laser pulses. The present study shall be quite useful to those working in the development of laser systems involving one or several electro optic switches.

2. Design considerations: Theoretical background

The shielding effectiveness (SE) (Thomas *et al* 2001, Olyslaser *et al* 1999, Mardiguian 1992) of any barrier is a measure of its ability to control radiated electro-magnetic energy. SE may be defined as logarithmic ratio of the power radiated in absence of the shield (P_o), to that in presence of the shield (P_s), measured at the same point in same operating condition. It is expressed in dB as

$$10\log_{10}(P_o/P_s) \text{ or } 20\log_{10}(E_o/E_s), \tag{1}$$

where E_o and E_s are the electric fields corresponding to P_o and P_s respectively. For practical measurements, SE can be expressed as the ratio of the voltage induced on the same impedance probe, measured in the two cases, as

$$20\log_{10}(V_o/V_s). \tag{2}$$

While designing an enclosure for a circuit, the following parameters should be considered: (i) material for EMI shield (governed by the type of noise, whether it is dominant by electric field E or magnetic field H; (ii) size (governed by the geometry of the experimental set-up); (iii) thickness of the metallic plates forming enclosure; and (iv) various apertures for different practical purposes and presence of unwanted seams/slots. While the size of a practical enclosure may simply be chosen as per the size of the object to be kept inside, the thickness of metal plates of an enclosure is determined by required mechanical strength. The presence of various desirable apertures and unwanted seams/slots, etc are critical and the deciding factors for SE of a practical enclosure, once the material of shield is chosen. These criteria are discussed below.

2.1 *Shielding effectiveness of a metal barrier*

The shielding effectiveness (Mardiguian 1992, Thomas *et al* 2001, Olyslaser *et al* 1999) of a solid metallic barrier of finite thickness is primarily the sum of reflection loss (R_{dB}) and the absorption loss (A_{dB}) of the EMI noise wave. The total shielding effectiveness ($SE_{t(\mathrm{dB})}$) of a metal barrier may therefore be expressed, assuming negligible multiple reflection loss, as

$$SE_{t(\mathrm{dB})} = R_{\mathrm{dB}} + A_{\mathrm{dB}}. \tag{3}$$

The reflection loss (R_{dB}) depends on the mis-match between the wave impedance (Z_w) and shield impedance (Z_{shield}). For a large impedance mis-match, the reflection loss will be larger, and it may be expressed as (Mardiguian 1992)

$$R_{\mathrm{dB}} = 20\log_{10}\left(\frac{|Z_w|}{4|Z_{\mathrm{shield}}|}\right), \tag{4}$$

where $Z_w = E/H$ and $Z_{\mathrm{shield}} = \sqrt{\omega\mu/\sigma}$. The shield impedance Z_{shield} is governed by frequency and material parameters, and for aluminum at 100 MHz, it comes out to be $\sim 0{\cdot}005\ \Omega$. On the other hand, the wave impedance Z_w is dependent on the relative distance (z) between the source and the barrier compared to the wavelength (λ) of the radiation. In the near field ($z \ll \lambda/2\pi$), the Z_w may be approximated as

$$Z_w = 18000/fz \text{ (for E-dominant wave)}, \tag{5}$$

$$\text{or } Z_w = 7{\cdot}9fz \text{ (for H-dominant wave)}, \tag{6}$$

where f is the frequency in MHz, and z is in meters. In the far field ($z \gg \lambda/2\pi$), the EMI noise is always dominated by the E field, and Z_w becomes independent of source distance (z) and frequency (f), and its value is equal to 377Ω. The reflection loss for a good conductor (like copper, aluminum) in the far field becomes close to $\sim$ 85 dB for electro-magnetic radiation of 100 MHz frequency. In the near field, due to higher impedance, the reflectivity for E field is even higher than in the far field case, and it becomes close to 99 dB at z of 10 cm. However, for H-field, due to lower impedance, the reflectivity in the near-field becomes smaller than in far-field case. Hence, it is very easy to shield the electric noise at low as well as high frequencies due to high reflectivity, but difficult to shield low frequency magnetic noise due to its low reflectivity.

The absorption loss (A_{dB}) for a metal barrier of thickness (t) can be expressed as

$$A_{\text{dB}} = 8{\cdot}69t/\delta, \tag{7}$$

where δ is the skin depth. The latter depends on the conductivity (σ) of the barrier material, its dielectric constant (ε), permeability of the shield material (μ) and the frequency ($\omega = 2\pi f$) of the incident radiation. For good conductors ($\sigma/(\varepsilon\omega) \gg 1$), skin depth may be expressed as

$$\delta = \{2/(\sigma\mu\omega)\}^{1/2}. \tag{8}$$

It may be noted from (8), that the skin depth is independent of the type of noise (E, H, EM) but strongly depends on frequency. At high frequencies, δ becomes small and the absorption loss becomes high (i.e. better shielding). On the other hand, at low frequencies δ becomes large and absorption losses become low. While this is not a problem for E or EM wave because the reflectivity is high, for H-field due to the corresponding low reflectivity, this may pose a difficulty in achieving desired SE. If low frequency magnetic shielding is crucial, the only way out is to lower the skin depth by using a high permeability material like iron or mu metal. In the low reflection, low absorption cases, multiple reflection loss may also occur for a finite thickness metal enclosure. However, in a practical metal enclosure for E dominant noise or plane wave (EM), this may be neglected.

The SE of a given metal barrier, calculated using (3) to (8), is the highest achievable shielding effectiveness for a given set of parameters. However, in most practical cases, metallic enclosures would have various apertures, slots, uneven seam joints, etc. The presence of these apertures reduces the SE value as discussed below.

2.2 *Effect of apertures, seams and joints on SE*

Practically, in a shielded enclosure, it is necessary to have various apertures (Mardiguian 1992, Thomas *et al* 2001, Olyslaser *et al* 1999) e.g., for inserting various cables, laser beam propagation, etc. Due to the presence of a slot or a hole, an enclosure provides a poor shielding to EMI noise. The SE of an enclosure in the presence of multiple apertures and circular waveguide may be expressed as

$$SE_{\text{encl}}\ (\text{dB}) \approx 20\log_{10}(\lambda/2d) - 10\log_{10} n + 32t/w, \tag{9}$$

where d is the maximum linear dimension of an aperture (diameter for a hole or length for a slot), n the number of apertures within a distance of $\lambda/2$, and t/w the thickness (t) to width (w) ratio for a circular waveguide (extended or loaded hole). It may be mentioned that an array of similar adjacent apertures (such as in a wire mesh, or array of slots/holes, etc.) behaves like a single aperture if their separation is much less than the aperture width (Mardiguian 1992). In addition to the slots necessary for instrumentation purpose, the seams in the enclosure also act like slots. The apertures act like antennae to radiate energy in/out of the enclosure. The efficiency of this coupling depends on the size of the aperture compared to λ of the interference noise. A thumb rule (Mardiguian 1992) to follow in general design is to avoid openings larger than $\lambda/20$ for standard commercial products ($\lambda/50$ for military products). Since most EMI coupling problems are broadband in nature, the frequency of concern would be the highest frequency within the bandwidth envelope. For all lower frequency components, the condition is automatically satisfied. For example, for upper limit of noise frequency of 200 MHz in our case, which corresponds to λ of 1·5 m, the opening size should be less than 30 mm. Since seams also act like slots, they should be connected (by screws) at distances smaller than the above value. The details and the performance characteristics of our EMI shielded enclosure for Pockels cell for use in re-generative amplifier are given below.

3. Description of enclosure and its shielding effectiveness

The metallic (aluminum) enclosure (figure 1) used in our study consisted of six aluminum plates of 6 mm thickness assembled in a cuboidal shape to make a box of dimensions of 120 mm × 140 mm × 145 mm. Among the two materials of large conductivity, copper and aluminum used for effective shielding, the latter was chosen to reduce the cost and weight of the enclosure. Of the six plates, four were welded and the remaining two plates (the top plate and a side plate) were kept demountable for installing the Pockels cell and high voltage switching circuitry. Welding provides good electrical contact between the metal plates and also ensures that there are no slots left to radiate out any noise. The demountable plates were attached to the main box using screws at a spacing of 25 mm, as determined from the thumb rule of $\lambda/50$ (military grade) at the highest frequency (200 MHz) involved in our set-up. As mentioned earlier, the joints between demountable plates were overlap type instead of standard butt type to minimise any leakage through them. This enclosure had five clear holes, of which two holes of 20 mm diameter were meant for laser beam entry and exit, and the other three of 15 mm diameter were used for inserting various coaxial cables carrying trigger signals and for power supplies. The holes for laser beam propagation were loaded with circular wave-guides, each of 25 mm length and 20 mm inner diameter, in order to further reduce the leakage of electromagnetic radiation through these holes (as per the third term

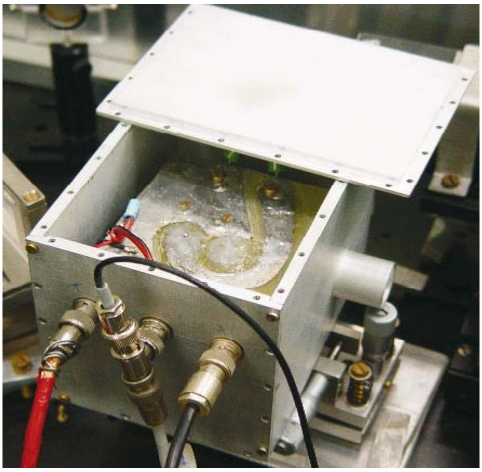

Figure 1. Photograph of the EMI shielded enclosure.

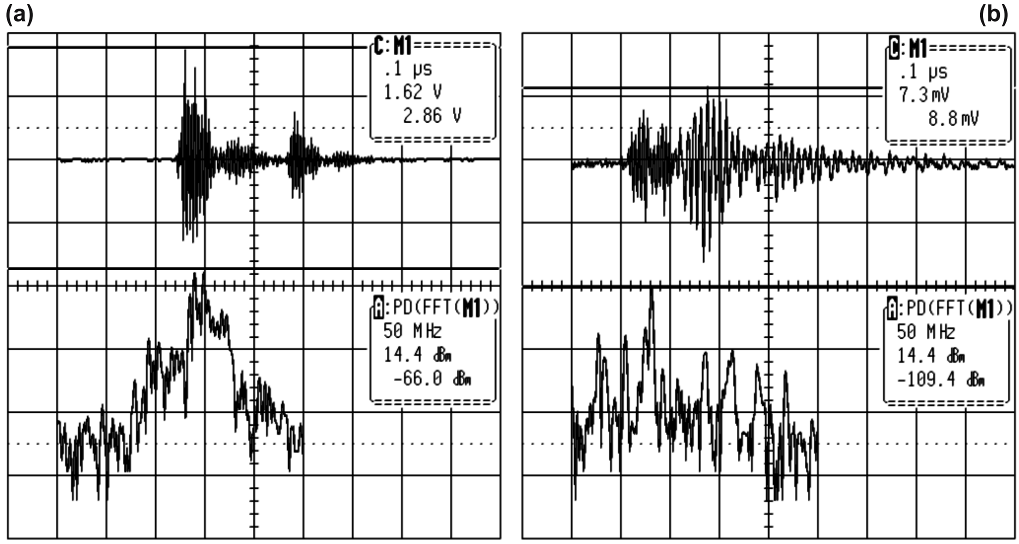

Figure 2. EMI noise signal (top) and its Fourier transform (bottom) with: **(a)** open lid condition; **(b)** closed lid condition of enclosure.

in equation (9)). Although a longer length of wave-guide compared to aperture diameter is desirable to achieve higher SE value, this could not be done due to limitation of available space. For the slots dimension (d) of 25 mm, thickness and width ratio (t/w) of a circular wave guide of 1·25 and the number of circular apertures (n) of 5 in a designed enclosure, using (9) one calculates the SE of ~65 at 150 MHz frequency.

Based on the above described design, four enclosures were fabricated one each for pulse selector, pulse injector, pulse ejector and pulse cleaner units of Nd:glass regenerative amplifier (Sharma *et al* 2005). The regenerative amplifier was seeded with one of stretched laser pulses (~250 ps duration) from 100 MHz pulse train from cw mode-locked oscillator (GLX 200 from Messrs Time-bandwidth Products, Switzerland) and grating pair based pulse stretcher unit. Pockells cells were connected to high voltage switch (Behlke HTS-50-08 with 5 ns on time) circuitry energized by a DC power supply up to 3·8 kV and a 5 V DC power supply to control the triggering. The Behlke switches were triggered using a fast electric pulse of 10 V, 10 ns (FWHM), generated by a pulse synchronization circuit of the laser control unit. A home-made high impedance pick-up probe (or E-probe) was used for measurements on radiative emi noise. It consisted of 25 cm long copper wire of 2 mm diameter (acting as rod antenna) connected to a RG-58 coaxial cable of length ~1 m, and the signal displayed on an oscilloscope. This probe was kept at a distance of 30 cm from the noise source and pick up signal was displayed on a 500 MHz digital storage oscilloscope (Lecroy 9350). The effectiveness of the enclosure for EMI shielding was studied under open and closed lid condition. While the electro-magnetic noise signal was measured to be ~2·9 V in the open lid condition, it reduced to ~9 mV in the case of closed lid. The noise signal level in the absence of any enclosure was also found to be nearly same as that for the enclosure with open lids. The recorded noise signals (open lid, closed lid) along with their Fourier transforms are shown in figures 2a and 2b respectively. The overall shielding effectiveness parameter thus turns out to be about 50 dB (i.e., attenuation of the noise by a factor of 325). This reduction of noise by 50 dB could also be seen clearly by comparing the Fourier transform of the noise signals in the two cases. The shielding of 50 dB

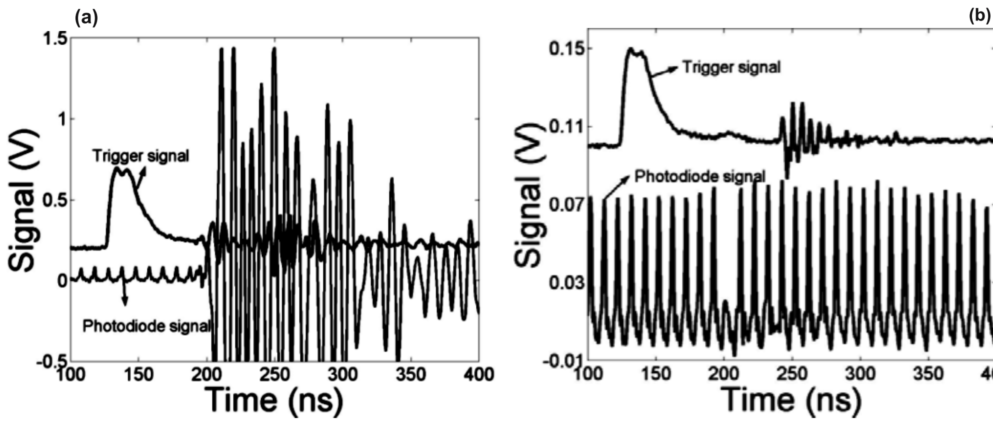

Figure 3. Rejected laser pulse train and trigger signal to Pockels cell of laser pulse selector unit: **(a)** in open lid condition; **(b)** in closed lid condition of enclosure.

was sufficiently good to overcome the problem of spurious triggering of other Pockels cells and electro-magnetic compatibility of detector circuits.

The performance of the enclosure for the laser pulse detector circuit was demonstrated by recording laser pulses at a repetition rate of 100 MHz, in the open lid and closed lid conditions. Figure 3a depicts the electrical trigger signal and the optical pulse train obtained using a fast photodiode in open lid condition. This figure clearly shows the presence of large radiated noise picked up by the photodiode circuitry, resulting in meaningless detection of the pulse train. When the lids of the enclosure were closed, the pulse train with one missing pulse (i.e., the laser pulse selected by the laser pulse selector unit) with respect to the trigger signal was clearly observed as shown in figure 3b, demonstrating the adequate shielding effectiveness of the enclosure.

In the present study, the SE of 50 dB for our enclosure is smaller than the calculated value of 65 dB. This may be due to the presence of uneven joints between the plates or EMI coupling due to different coaxial cables. Various coaxial cables, energizing the Pockels cells may couple energy contained in the enclosure and radiate it outside, or bring currents generated by external fields into the enclosure to cause interference. Therefore, the SE of the enclosure may be enhanced by making uniform electrical contact between the mating seams using conductive gaskets and improving the coaxial cable entry design.

4. Conclusion

EMI shielded box for Pockels cells was fabricated and tested for its EMC against any radiative electro-magnetic noise in the high voltage, fast switching environment of a laser re-generative amplifier set-up. The shielding effectiveness of the enclosure was measured to be $\sim$50 dB, which was found adequate for EMC of nearby placed electronic circuits. It prevented any spurious triggering of other HV switches of the re-generative amplifier or any noise addition to the measurements with photo-diode detectors. The enclosures were also quite effective in preventing spurious triggering of the Pockels cells by the EMI noise generated in firing of the flash lamps in the laser amplifier.

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