FastPulse Technology, Inc.

LASERMETRICS® Division

220 MIDLAND AVENUE
SADDLE BROOK, NEW JERSEY 07663
TEL (973) 478-5757
FAX (973) 478-6115
Web Sites: www.lasermetrics.com
www.fastpulse com

USER'S GUIDE

FOR BBO, KD*P, RTP & LITHIUM NIOBATE

Q-SWITCHES & MODULATORS

FOR Q-SWITCHING, CHOPPING & PULSE EXTRACTION

This guide is a work-in-process. It is updated and, hopefully, improved with new information as it becomes available and to answer questions posed by readers. The author welcomes suggestions, corrections, clarifications and other inputs which may be incorporated into the Guide.

ROBERT L. GOLDSTEIN

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1.0 GENERAL DISCUSSION

KD*P, BBO, RTP and Lithium Niobate Electro-Optic Modulators (EOMs) and Q-Switches (QS) are electro-optic crystal devices that operate by virtue of the linear electro-optic (Pockels) effect. The effect results in rotating the plane of polarization of a linearly polarized beam propagating through the crystal in response to an applied electric field. The direction of the electric field with respect to the direction of the beam in the crystal is one way of classifying the type of device. All the devices discussed here are EOMs and some EOM models are specifically configured to be used as EOQS's.

KD*P crystal EOMs may have their electric fields applied parallel to the direction of the laser beam (longitudinal devices) or orthogonal to the beam (transverse devices). BBO, RTP and Lithium niobate crystals are almost always used in the transverse mode and the resulting devices are therefore called transverse field modulators.

1.1 LITHIUM NIOBATE DEVICES

Lithium niobate is noted for its low absorption in the red through near infra-red spectrum. It is thus capable of tolerating high average power through-put. With appropriate antireflection coatings, it is particularly well suited for operation in the 850 to 3500 nm spectral region. When utilized as a Q-switch, $LiNbO_3$ is highly efficient and can tolerate peak power densities up to 350 MW/cm^2. In CW laser applications, it has been used as a modulator and power controller at average powers in the order of 100 watts in a 6 mm beam diameter.

Lithium niobate offers some advantages over Q-switches fabricated from deuterated KDP (KD*P) and its isomorphic crystals: lithium niobate is not hygroscopic and thus does not require windows and a sealed housing to protect the crystal from atmospheric moisture; it is not subject to an ion migration effect that can damage KD*P by long-term application of DC voltages. Another advantage is the lower voltage requirement of the typical lithium niobate device (9x9x25 mm) which, at 1064 nm, has quarter wave voltages in the 1.5 kV range compared to KD*P which has a 6.5 kV requirement.

Lithium niobate has a large piezo-electric constant which can interfere with Q-switching and modulation. Techniques for dealing with this characteristic are discussed in later paragraphs. While lithium niobate is not water soluble and can be used in the open air, without a protective housing or sealing by antireflection coated windows, the user must insure that the crystal surfaces are clean and devoid of dust particles and other deposits. Under the influence of high electric fields, the crystal will attract dust, oil particles and other airborne materials to its polished, antireflection coated surfaces. These particles act as low threshold damage sites which will degrade and cause permanent damage to the antireflection coatings on the crystal surfaces.

The safe maximum peak power density rating of 350 MW/cm^2 can only be achieved with scrupulously clean surfaces. "Hot Spots" in the laser beam must be avoided since their peak power density can easily exceed the maximum rating by an order of magnitude. It is suggested that for most applications the safe operating level be limited to 200 - 250 MW/cm^2 to provide a factor of safety in the event of hot spot formation or changes in the laser cavity that might lead to a sudden increase in peak power density.

Lithium niobate can be utilized at wavelengths shorter than 600 nanometers if a specially formulated crystal (MgO doping) is specified. At wavelengths $<$600 nm, undoped crystals may be damaged by even low power (1-2 milliwatts) laser beams. The damage is cumulative and appears as localized variations in the refractive indices.

1.2 KD*P (Deuterated KDP) DEVICES

KD*P (and crystals in the same family) have been used for Q-switching and modulation since the advent of lasers. KD*P (KD_2PO_4) crystals, also referred to as DKDP, have very high optical damage thresholds. Two types of Pockels cell devices can be constructed with KD*P:

1. KD*P Transverse field modulators (TFM) are generally configured as small aperture, low voltage modulators. Because of their low voltage requirement, some may be used at driving frequencies up to 100 MHZ. TFMs may also be used in laser pulse gating, slicing, chopping and shaping applications where the original laser pulse must be shaped or controlled in some desired manner.
2. Longitudinal field modulators (LFM) are designed so that the electrodes produce an electric field parallel to the direction of light propagation. Longitudinal devices are used mainly as Q-switches and shutters and can be fabricated with large apertures; clear apertures up to 75 mm have been produced. With appropriate electronic drivers, LFMs can be used for pulse gating, chopping and shaping, where nanosecond transition times are needed.

KD*P exhibits low absorption throughout the near-UV, visible and near IR spectrum. Q-switches utilizing KD*P are capable of withstanding high peak power density pulses. At 1064 nm typical units can tolerate up to $\approx$ 850 MW/cm^2 in a Q-switched pulse of $<$10 nanoseconds width with a uniform beam power density profile (i.e., no "hot" spots"). As pulse width decreases, peak power density tolerance increases to about 20 GW/cm^2

Max. for pulses in the 100 femtosecond range. These same ratings apply throughout the visible spectrum and should be considered absolute maximum ratings for the given pulse width range.

KD*P (and its isomorphic crystals KDP, ADP and AD*P, etc.) are water soluble and must be protected from moisture. This is accomplished by optical windows which seal the housing containing the crystal. The fused silica windows are usually anti-reflection (AR) coated on the exterior surfaces and an index matching fluid is used internally to reduce reflections from the polished crystal surfaces and interior window surfaces. Vacuum deposited AR coatings are seldom applied directly to the crystal surfaces since they deteriorate when exposed to high optical intensity beams and electric fields. Sol gel AR coatings have proven to be the most suitable AR coatings directly applied to the crystals. Sol gel coatings have power density ratings equal to or greater than the crystal materials on which they are deposited. They also provide highest transmission efficiency and broad bandwidth.

When using a Q-switch, the user must insure that the device surfaces are clean and devoid of dust particles or other surface contaminants. The maximum peak power density rating of ≈850 MW/cm^2 (10 nanosecond pulse widths) can only be achieved with extremely clean surfaces. If there are any "hot spots" in the laser beam, their peak power density must be held well below the absolute maximum rating.

1.3 RTP DEVICES

Rubidium Titanyl Phosphate ($RbTiOPO_4$) or RTP is a very useful new crystal material for electro-optic modulators and Q-switches. It combines several desirable features of KD*P and Lithium Niobate and has one major advantage over both of them: RTP exhibits an extremely low piezoelectric effect; there is essentially no ringing superimposed on the transmitted optical beam passing through the crystal. This characteristic permits the use of RTP at Q-switching high repetition rates (~100 kHz). At this time, no other crystal material provides ring-free operation at attainable low voltages and high repetition rates.

RTP is non-hygroscopic and has a transparency range from 350 nm to 4300 nm. With antireflection coated surfaces at 1064 nm, transmission is >98.5%.

Damage threshold of RTP is of the same order as highly deuterated KD*P, approximately 600 to 850 MW/cm^2 for a 10 nanosecond wide Q-switched pulse at 1064 nm. RTP crystals do not exhibit “gray track” laser damage, which is a primary limitation of KTP crystals. However, recent testing showed that at wavelengths at or below about 532 nm a non-linear absorption/emission effect may occur with input power densities greater than about 10 W/cm^2.

Typical extinction ratios for RTP Q-switches are greater than 100:1 (>20 dB), measured at 633 nm. Thermal stability is excellent over a broad temperature range which is the result of a thermally compensating two-crystal opto-mechanical design.

Drive voltages for RTP are lower than those of Lithium Niobate in the same aperture sizes. For an 4 mm clear aperture device having a crystal path length of 20 mm, the ½ wave retardation voltage is about 1.6 kV at 1064 nm. For many applications, which require operation at ¼ wave retardation, the resulting voltage requirement is less than 1.0 kV.

Operation of RTP (Series 1147) devices allows the input plane of polarization of the laser to be either parallel or perpendicular to the plane of the modulator’s electrical terminals. Setup and alignment procedures for RTP devices follow the same routines given for KD*P and lithium niobate Q-switches and modulators.

Note that the isogyre figures for RTP can be identical to those produced by KD*P and Lithium Niobate in the same optical setups. However, intrinsic birefringence may not be completely canceled when aligning the two crystals for best performance; residual birefringence is the limiting factor in attaining high extinction ratios.

1.4 BBO DEVICES

Beta Barium Borate (Beta-BaB_2O_4), or BBO is finding use in Q-switches and Laser Pulse Gating/Picking Systems in the 500 nm to 1100 nm range. It is also useful in regenerative amplifier pulse seeding, extraction and chopping applications. The material has a very low piezoelectric response which makes it useful at high repetition rates (50 – 100 kHz). BBO devices require much higher drive voltage than either KD*P or RTP. For equivalent aperture sizes, BBO may require more than10X the voltage needed by RTP for the same optical retardation at a given wavelength. A BBO crystal (3 X 3 X 20 mm) will generally exhibit an extinction ratios in the range of 1000:1 at 633 nm.

Because of the high voltages required and short distance between electrodes (6 mm for a 5.5 mm aperture device), applied DC voltages should limited to less than 1kV/mm of clear aperture. Exceeding this value may result in an arc between electrodes which may permanently damage the crystal. Pulsed voltages can exceed this value if the pulse width is limited to about 10 μs.

BBO electro-optic devices operate in the TFM configuration. For smaller apertures, up to about 6 mm, one crystal of up to 25 mm length may be used. For larger apertures a two crystal layout is often used since it is difficult to grow large cross section crystals with lengths greater than 25 mm. Both aperture and length dimensions are presently limited by crystal growth dynamics (similar growth problems exist for RTP crystals.)

Unlike RTP, BBO is slightly hygroscopic; a polished surface, exposed to the open air, will eventually become fogged. To overcome this characteristic, BBO crystals are often packaged in sealed enclosures with protective fused quartz windows which are generally supplied with antireflection coated windows. Bare, un-enclosed crystals may be used when a protective, water vapor barrier coating is applied to the polished crystal surfaces. Such coatings may also function as antireflection coating but they may also reduce the crystal's maximum attainable damage threshold which is in the same range as KD*P.

1.4 INTENSITY MODULATION

Intensity modulation of an incoming beam requires that the beam be linearly or circularly polarized, ideally have a narrow wavelength bandwidth ($< \pm 10$ nm) and low divergence/convergence (<3 arcminutes full angle). The limiting factor is the crystal's piezoelectric response which prevents uniform depth of modulation over a wide range of driving frequencies. Lithium niobate devices are rarely used for broadband high frequency modulation applications.

For pulse chopping of CW laser beams and extraction of single or multiple pulses from a CW or Q-switched modelocked laser, the piezoelectric response can be minimized by driving the lithium niobate and KD*P with differential pulse voltages. This technique will provide pulse widths from about 4 nanoseconds up to approximately 50 nanoseconds with minimal ringing. The exact maximum pulse width depends on the crystal dimensions while the minimum width depends on the rise and fall times of the electronic driver.

KD*P devices have been used for broad band modulation at frequencies in excess of 100 MHZ. The higher frequency devices are generally of the transverse field type since they can operate at lower voltages than the longitudinal types. TFMs have higher capacitance than LFMs but their advantage lies in the lower drive voltages and reduced driver power. This power is a function of the square of the applied voltage and only the first power of the capacitance. KD*P LFMs are used typically where large aperture devices are required at frequencies up to 100 kHz. While piezoelectric response is present in KD*P, it is typically much lower in amplitude than with lithium niobate.

Pockels cells are essentially passive, capacitive devices. When such a cell is connected to a coaxial cable, the cell capacitance may act as an electrical impedance discontinuity. When driven with high voltage, high speed pulses or other waveforms, the voltage steps can cause electrical ringing in the cable and radiation of radio frequencies or pulses (RFI, EMI). Therefore, some means of shielding may be necessary. As a temporary expedient, aluminum foil can be used as a shielding material. Electrical terminals must be well insulated and the foil must be grounded.

CAUTION: Protective laser goggles should be worn during alignment procedures.

2.0 EOM SETUP AND ALIGNMENT

Lasermetrics Modulators and Q-switches are supplied with a marker on one of the stainless steel aperture plates or on the outer housing to indicate the preferred plane of polarization of the incoming beam. The plane of polarization must be aligned with the marker (or rotated 90^o from it) for correct operation. If the marker is missing, the appropriate directions must be inferred from the crystal geometry by viewing the sides of the crystal through the clear aperture. In general, for KD*P LFMs, the input polarization plane must be parallel to a line which was drawn on the circumference of the crystal during fabrication (X crystallographic direction). For lithium niobate the polarization plane must be perpendicular to any one crystal side. For ADP and KD*P TFMs, the polarization plane must be at 45^O to any crystal side. For many devices, the electrical terminals act as a marker for correct alignment of the incoming linear polarization plane.

It is strongly recommended that initial alignment of be done with a low power (0.5 to 2 milliwatts) He-Ne laser to assist in visualizing beam position. If alignment must be done with only an IR laser, the power of this laser must not exceed 5 milliwatts. At higher power levels, it is possible to damage the device if the beam strikes the internal electrodes thereby causing thermal damage. Unless there are strict constraints on space and positioning devices, the device should be mounted in a gimbal that provides accurate and stable pitch and azimuth adjustments. Some means for obtaining horizontal and vertical translation is usually necessary to center the device on the input laser beam.

If the device is being used in a laser cavity, it is recommended that the alignment be done with a He-Ne laser having its beam centered on and coaxial with the laser rod. If convenient and safe, the coaxial condition should be ascertained by operating the laser with the He-Ne to confirm that the beams are indeed coaxial. If this cannot be done safely, then the He-Ne beam should be retro-reflected off the nearest laser rod surface back onto itself using a pin hole in front of the He-Ne. It is essential that the laser beam pass through the EOM entrance and exit apertures without vignetting. The beam should be centered in both apertures with at least 0.5 mm clearance all around.

The following procedure has been shown to be most reliable for obtaining optimum alignment. The object is to center the laser beam in the device apertures and then generate an optical pattern which accurately locates the optical axis of the crystal with respect to the laser beam. This will probably require several adjustments of pitch, azimuth and translation to optimize the alignment but it will provide positive, visual confirmation of the alignment. The procedure requires two linear polarizers. If the alignment is to be done inside a laser cavity incorporating only a single polarizer, then an additional polarizer (used only for alignment) may be of the Polaroid type -- typically HN-32 or HN-38.

1. Remove any polarizers used to polarize the beam entering the device. If the laser is already polarized it does not effect this procedure. Position the EOM in the He-Ne laser beam to center the through the apertures without touching the aperture edges.

2. Place a light colored card in the path of the beam at a distance of about 8 to 12 inches from the exit aperture of the EOM. If the EOM is located within a laser cavity, the card should be placed against the laser rod holder and a small hole made in the card to locate the rod aperture. Mark the beam location on the card with a circle or dot and leave the card in place.

3. Place the input polarizer in the beam with its polarizing axis aligned to the mark on the device. It is assumed that the polarizer does not angularly deviate the beam. Locate the output polarizer (analyzer) at the output side of the device and insure that its polarizing axis is rotated 90° from that of the input polarizer.

4. Place a strip of frosted adhesive tape (Scotch Magic Mending Tape or similar material) over the device entrance aperture. Gently press the tape in place. A lightly frosted glass plate is preferred over the frosted tape since some brands of tape are slightly birefringent. The frosted glass will provide the same scattering but must be as close to the entrance aperture as possible. A pattern, or some part of it, will be projected on the card. This is called an isogyre pattern as illustrated in Figure 2 below. <u>When the tape is in place, the laser beam may become so diffused that the central spot may not be visible on the card.</u> <u>Do not move the card</u>. If is usually safe to assume that the spot is really there, in its original position.

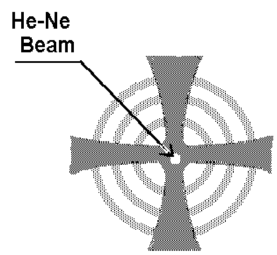
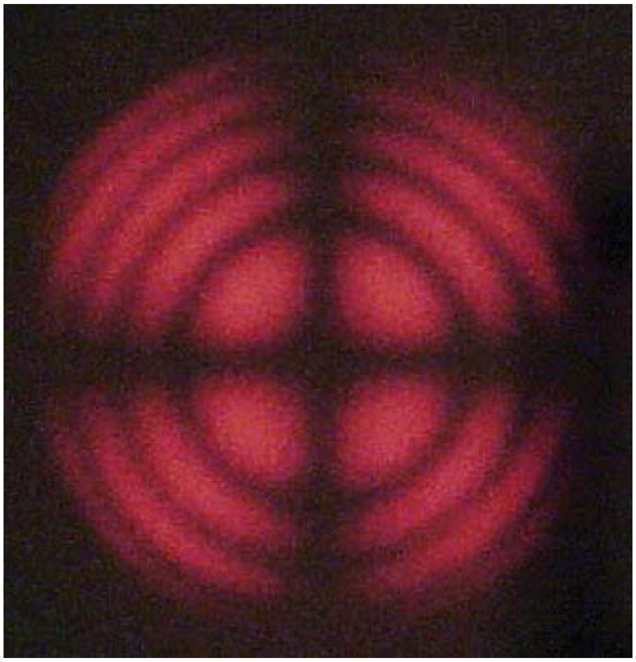


Figure 2: Isogyre pattern with beam centered

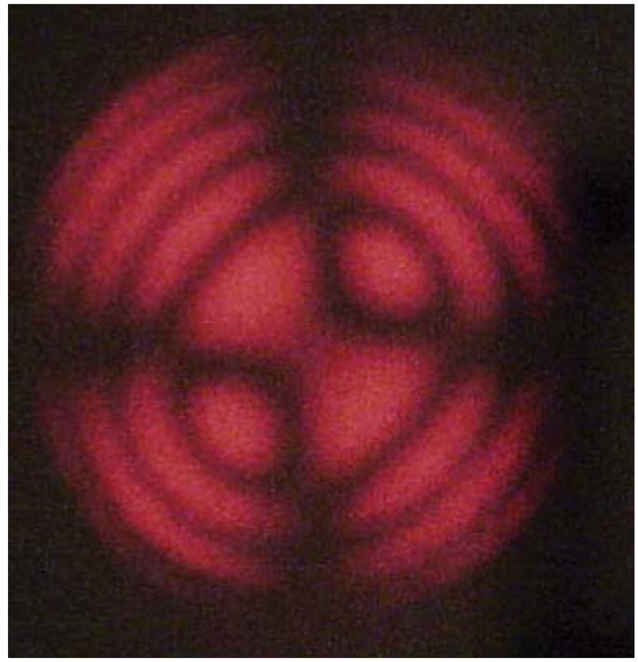
The isogyre is a representation of direction through the crystal, not position on a surface.

If the beam direction is not parallel (within a few degrees) to the optic axis, the beam will form incomplete, distorted isogyre patterns. If the beam is parallel to the optic axis, the pattern of Figure 2 will result when there is no voltage present. Refer to the following page for photos of isogyre figures with typical voltages applied.

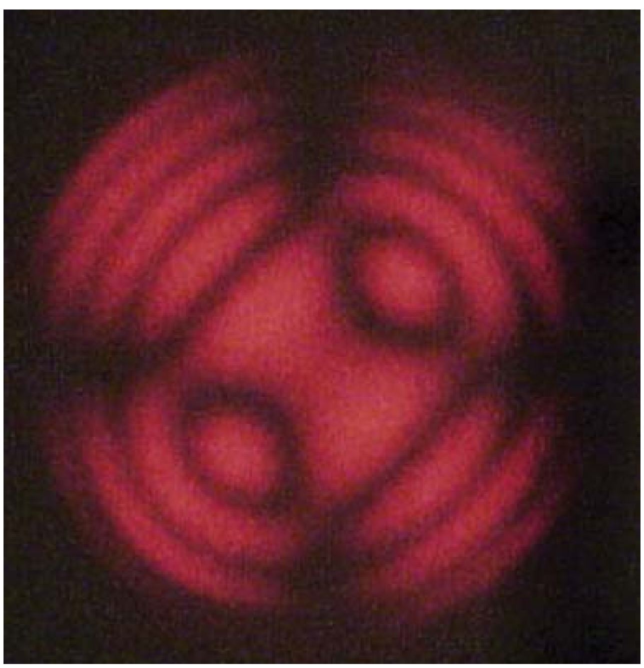
This alignment procedure works with all devices utilizing uniaxial crystals such as KDP, KD*P, ADP, lithium niobate and tantalate, etc. It is also useful with crystals such as KTP, BBO and RTP.



No Voltage Applied



1 kVDC Applied



Quarter Wave Voltage, ~1.9 kVDC Applied

Half Wave Voltage, ~3.8 kVDC Applied

Fig. 2a Isogyre Figures for a Pockels Cell, Model Q1059PSG, between crossed polarizers in a divergent 633 nm laser beam; with zero voltage, 1 kVDC, 1/4 Wave and 1/2 Wave Retardation Voltages (DC). Note the clockwise 45^0 tilt axis of the pattern. If voltage polarity is reversed, the tilt axis will be at 315^0.

NOTE: These measurements are usually made in a darkened room after basic alignment and adjustments are completed. In most instances, the pattern to be viewed will be difficult to see in normal room lighting. For improved resolution and visualization, a ≤150 mm focal length lens can be used to collect light exiting the analyzer and to project the beam onto the card. Do not focus the beam to a fine spot. The lens should be positioned to produce a conveniently sized image on the card for viewing. If a lens is used, insure that the laser beam is centered and is not deviated from its original path. It is difficult sometimes to tell exactly which part of the pattern is being displayed when the beam axis is not closely parallel to the crystal optic axis. When this occurs, the modulator pitch and/or azimuth position must be varied until some identifiable portion of the pattern is visible. The alignment process can then be completed as in the following steps:

If the optical axis of the crystal is not parallel to the path of the laser beam, the isogyre pattern will be off-center and the device must be moved in pitch and azimuth. When the isogyre is centered over the circle or dot or hole in the card, this indicates that the device is well aligned , i.e., the crystal optic axis is parallel to the laser beam. After making any positional adjustments, the beam position relative to the device aperture stops must be re-confirmed.

The beam must propagate through both apertures without vignetting and with adequate clearance. If it does not, employ horizontal and vertical translation until clearance is confirmed. If the figure is not in the form of a cross, then the polarizers are not rotationally aligned to the faceplate mark or at 90° to each other.

After the cross of the isogyre is centered, the polarizers can be rotated slightly to maximize the darkness of the center of the cross. Once this is done, the device is not only aligned with the laser beam, it is also nulled with respect to the crossed polarizers for best contrast ratio and is ready for operation. When the modulator is in actual use, very fine adjustments of the pitch and azimuth controls can further optimize performance.

3.0 Q-SWITCHING CONFIGURATIONS

The three typical cavity configurations and their modes of operation are characterized on the following pages.

Two issues must be considered when selecting a mode of operation: piezoelectric response of the EOQS and ion migration. Both KD*P and lithium niobate have a piezoelectric response to applied voltage. KD*P crystals appear to undergo electrolysis when a long-term DC electric field is applied. Both problems can be dealt with satisfactorily - as discussed below in Section 4.

Laser systems with a KD*P EOQS operating in the "quarter-wave retardation" mode ($\lambda/4$) must have $\lambda/4$ voltage applied continuously to the Q-switch to prevent lasing (Figure 3). The voltage is switched to zero only during the time the Q-switched pulse is generated. In this type of system, it is particularly important to remove DC voltage when the system is in standby.

One alternative, implemented by several laser manufacturing companies, is to apply the $\lambda/4$ DC voltage to the Q-switch when the flash lamp is triggered. There is no voltage applied between the flash lamp firings or when the system is in standby. This technique can be used at repetition rates up to about 20 pps.

Generally, Q-switches used in the DC $\lambda/4$ mode have a shorter lifetime than those used in a pulsed mode where the switching voltage is applied as a brief pulse. For this reason, laser systems that operate for long periods of time (such as industrial lasers) should be designed for pulsed-quarterwave operation (Figure 4).

RTP Q-switches show neither piezoelectric or ion migration effects. Devices using this material are being specified in a growing number of critical applications. At the present time the major limitations of RTP are cost and available aperture size. Typical aperture sizes are in the range of 4, 6 and 9 mm.

REFERENCE

R. Goldstein, "Electro-Optic Devices in Review", Lasers & Applications, April, 1986. (Available for viewing and downloading from our web site: www.fastpulse.com).

QUARTERWAVE (λ/4) OPERATION - (Fig. 3)

The quarterwave configuration illustrated in Figure 3, is the most economical, in terms of number of components used, and simplest arrangement for Q-switching with an electro-optic Q-switch. This configuration minimizes the DC high voltage level required for efficient Q-switching. It also permits operation of the laser in its conventional, non-Q-switched mode by simply removing high voltage from the Q-switch. As explained later (Para. 4.1) certain precautions must be observed.

The configuration employs a Q-switch and a single polarizer. λ/4 voltage must be applied continuously to prevent lasing. The voltage is switched to zero during the time the Q-switched pulse is to be generated.

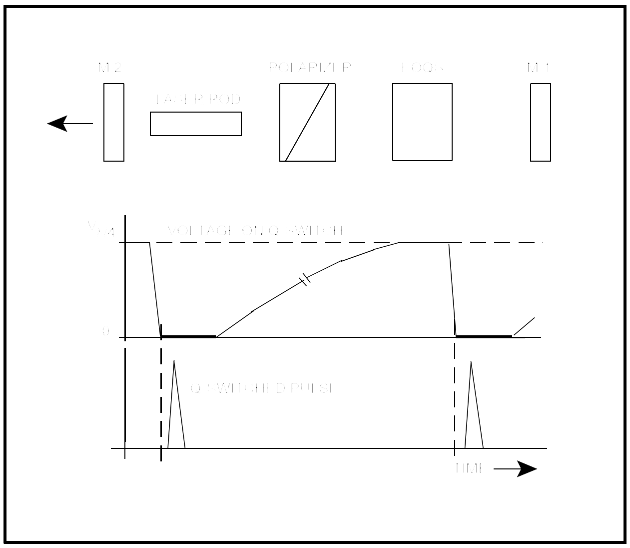


Figure 3. Quarterwave (λ/4) Configuration: DC λ/4 voltage is applied to prevent lasing. Voltage is then switched to zero volts to generate the Q-switched output pulse.

PULSED λ/4 OPERATION - (Fig. 4)

This mode requires a polarizer and quarterwave plate in addition to the Q-switch. The Figure 4 configuration of elements combines the best features of the half and quarter wave modes. A quarterwave plate is equivalent to applying static λ/4 voltage to the Q-switch crystal. Since voltage is applied only as a brief pulse, there is no DC voltage across the crystal, thereby extending Q-switch life indefinitely (para. 4.1). The only disadvantage is that the voltage pulse amplitude must be 20% to 25% higher than the static voltage used in Fig. 3.

Component Descriptions
M1 = 100% Reflective Mirror
M2 = Output Mirror (partially reflective)
EOQS = Electro-Optic Q-Switch or Modulator
λ/4 = Quarterwave Plate
Polarizer = Glan-Air Spaced Calcite Polarizer

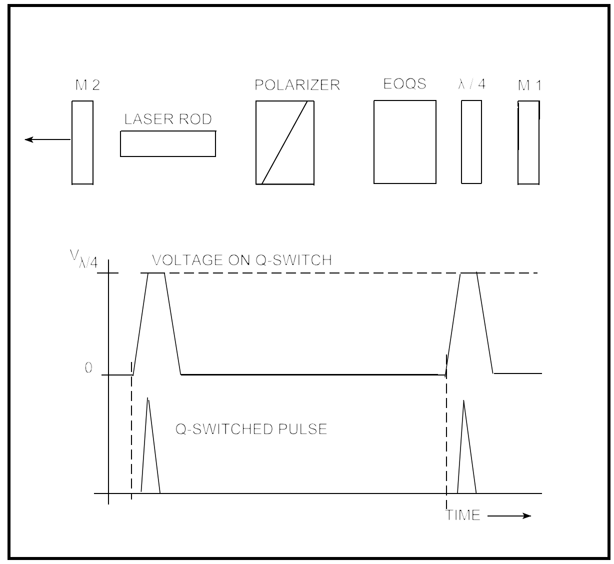


Figure 4. Pulsed Quarterwave Configuration: DC voltage is not required to prevent lasing.

HALFWAVE OPERATION - (Fig. 5)

This mode, illustrated in Figure 5, requires a Q-switch and two polarizers and thus is more expensive to implement than the quarterwave mode. Another disadvantage is that the halfwave voltage must be applied as a DC level which is switched to zero volts to generate the optical Q-switched pulse. The major advantage of using two polarizers is evident in high-gain cavities where the second polarizer provides improved holdoff of conventional lasing.

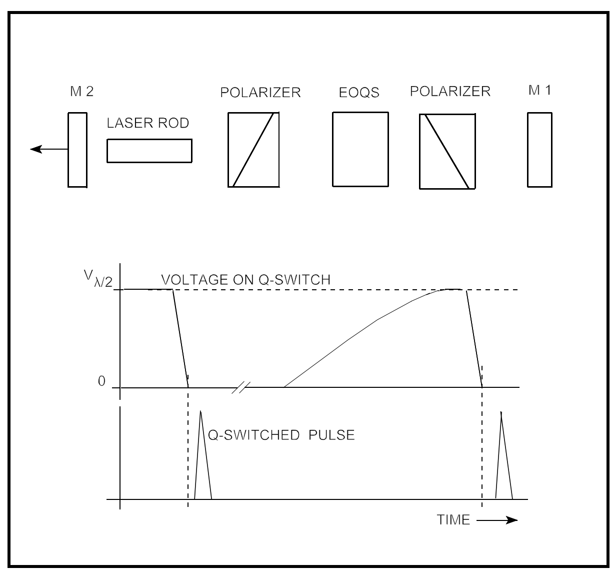


Figure 5. Halfwave Configuration: DC voltage is required to prevent lasing. Halfwave voltage is switched to zero volts to generate the optical Q-

switched pulse. In ruby lasers, one polarizer can usually be deleted -- the rod acts as a polarizer.

4.0 Q-SWITCHING PRECAUTIONS

Lithium niobate crystals exhibit a strong piezoelectric effect (KD*P to a lesser extent) that can have an adverse effect when Q-switching. The effect can be neutralized by appropriate timing of the electrical pulse to the Q-switch.

The piezoelectric effect becomes apparent when a crystal such as lithium niobate is excited by a fast rise time electrical pulse. Physically, the crystal is excited into mechanical oscillation--a contraction and extension that effects the indices of refraction. In the case of quarterwave ($\lambda/4$) switching, DC high voltage is applied to the crystal to prevent lasing; the voltage is then switched to zero volts to allow the Q-switched optical pulse to be generated. The piezoelectric effect, in the form of a damped oscillation or ringing, appears some time after the voltage is switched to zero level. The actual time at which the ringing occurs and the frequency of the ringing is dependent on the physical dimensions of the crystal. The larger the crystal, the lower the frequency and the longer the time period before ringing occurs.

For instance, the typical ringing frequency of the crystal used in the Model 3905 Q-switch is approximately 350 kHz and the ringing appears about 700 nanoseconds after the voltage pulse reaches the zero volt level.

The effect of piezoelectric ringing on the laser output may be the generation of multiple Q-switched pulses. If the stored energy remaining in the rod (after generation of the first Q-switch pulse) is insufficient to form additional Q-switched pulses, leakage of laser energy in the form of lower amplitude conventional mode pulses may occur.

The problem can be overcome by timing the leading edge of the electrical pulse which initiates Q-switching to occur after the peak of the flashlamp pump pulse. This can be experimentally confirmed by monitoring the electrical pulse to the flashlamp or the lamp light energy.

By varying the time delay between the start of the flashlamp pulse and the leading edge of the Q-switch driving voltage, the Q-switching action can be made to occur at a time when flashlamp energy has decreased to a level that will not support additional lasing and thus, no additional optical pulses will be generated until the next flashlamp pump cycle.

Usually, the timing can be chosen such that there is minimal or no decrease in Q-switched pulse amplitude. If the decaying flashlamp pulse has too much amplitude for too long a time after the peak, then secondary pulses will probably occur.

The usual solution to this characteristic is to shorten the trailing edge of the flashlamp pulse, make its decay time more rapid, or increase the time delay between flashlamp firing and generation of the Q-switched pulse.

4.1 OPERATION WITH DC VOLTAGE

Application of DC voltage to some Pockels cell Q-switches and light modulators for long periods of time may result in permanent damage to the electro-optic crystal(s).

Devices fabricated from KDP, KD*P, ADP and AD*P, in the presence of continuous (DC) high electric fields, are subject to an ion migration effect. With long term application of high voltage, the polished optical surfaces become fogged and etched. All crystal surfaces, including those under the conductive electrodes can be similarly effected. This may result in discontinuities between the crystal and electrode conductors. Application of AC electric fields, even those with a small net DC level, appear to minimize the effect and extend lifetimes dramatically.

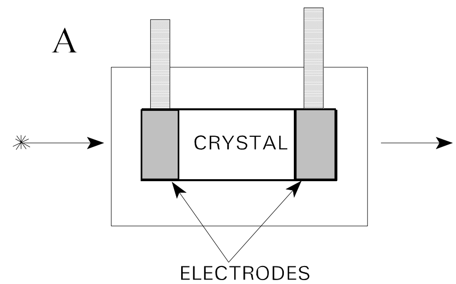
The effect is independent of the electrode materials used and has been documented for gold, indium, silver and transparent conductive oxide electrode materials. One manufacturer reports that a sustained voltage of 50 volts will eventually have an effect on the crystal. Use of inert index matching fluids does not mitigate the damage. The effect appears with or without the use of fluid.

We recommend that DC voltage not be applied to any Pockels cell when the laser system in which it is employed is not actively in use. When the system is in a standby condition, care must be taken to turn off the DC voltage to the Pockels cell. When this procedure is followed, operational lifetime of more than 5 years is not unusual and where this "voltage off" safeguard has been observed, many Lasermetrics Q-switches have been in active use for more than 20 years.

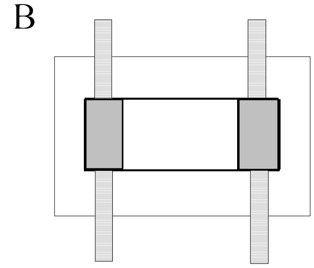
When Q-switching with pulsed voltages, it will be observed that the pulse amplitude must be greater than the DC voltage usually required. This is due to the “clamped electro-optic coefficient which is smaller than the normal value. Pulse amplitude will usually be 20% to 25% higher than the DC voltage value shown in the Pockels cell data sheet. The voltage level is somewhat dependent on the HV pulse generating circuit configuration.

Model 1041& 1043 Pockels Cell
Terminal Configurations - Figure 6

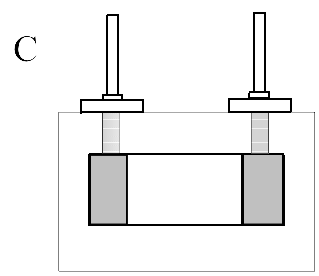
Configuration A: Copper tab leads for soldering directly to driving cable. This arrangement minimizes lead inductance and rise time. The Pockels cell is essentially a capacitor of ≈5 pf. Use minimum heating when soldering to leads.



Configuration B: Suitable for transmission line applications. The "straight through" arrangement allows attachment of the driving cable to one side of the Pockels cell and an output cable to the opposite side. The output cable is usually terminated with a resistor which matches the cable characteristic impedance, thus preventing electrical reflections.



Configuration C: Essentially the same as configuration A with pin terminals for ease of connection. The mating connectors are "pin plugs" which are supplied with the Pockels cell and are available from electronic supply stores.



NOTE: Q-switch Models Q1059P and 1058 are essentially identical to configuration Figure 6C. Electrical connections are solder pins for the 1058 Series and pin jacks (female) or pin plugs (male) for the Q1059P Series.

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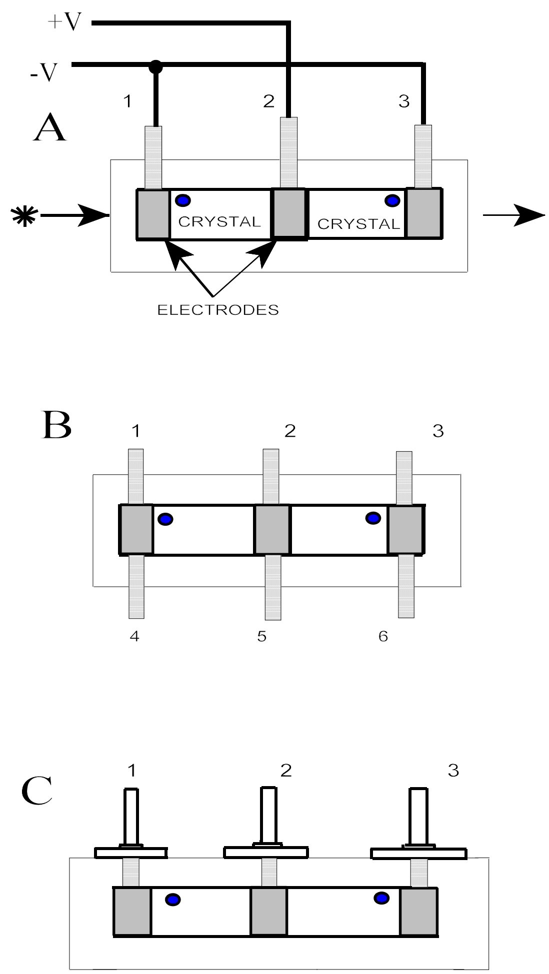
Models 1040-2X, 1042 & 1044 Pockels Cell Terminal Configurations - Figure 7

Crystals are optically in series and in parallel electrically. Note that for a given aperture size, housing & crystal dimensions are identical for all configurations. Dots on the crystals indicate positive direction of the Z crystallographic axis.

The dual crystal configuration reduces the required drive voltage by a factor of two compared to a single crystal device since each crystal contributes ½ of the polarization rotation necessary for rotating the input plane of polarization by 90^0.



Configuration A: Copper tab leads for soldering directly to driving cable. Typical electrical connection is: lead 2 connected to HV and leads 1 & 3 connected to ground or HV return. Polarity of these connections may be reversed. Tab leads minimize lead inductance. The Pockels cell is essentially a capacitor of ≈10 pf. Use minimum heating when soldering to tabs.

Configuration B: Suitable for transmission line applications. Electrical connections are same as above. The "straight through" arrangement allows attachment of the driving cable to one side of the Pockels cell and an output cable to the opposite side. The output cable is usually terminated with a resistor which matches the cable characteristic impedance, thereby minimizing electrical reflections.

Configuration C: Essentially the same as configuration A with removable pin terminals for ease of connection. The mating connectors are 2 mm "pin plugs" which are supplied with the Pockels cell or are available from electronic supply stores.

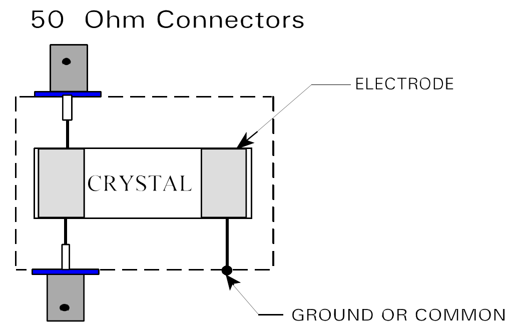
50 OHM POCKELS CELLS

The typical Pockels cell electro-optic light modulator / Q-switch is a capacitive device. That is, it approximates a lumped capacitance having its crystal dielectric material located between two electrodes. Many Pockels cells sold with 50 Ω connectors are incorrectly designated as 50 Ω devices. The connectors are used only to provide convenient connections to the crystal electrodes and external coaxial cables.

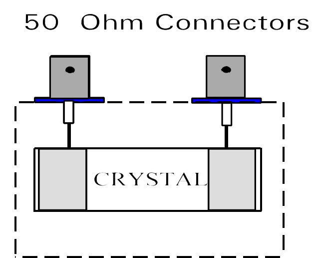
Figure 8 shows several configurations of this genre. In many cases, the connectors are chosen for their high voltage hold-off characteristics and may in fact be 75 Ω connectors (such as the MHV series). Connectors are sometimes specified only because of safety issues - to prevent exposure to open high voltage connections.

In Figure 8 configurations, no attempt is made to impedance match the connectors to the crystal. These devices are basically capacitors with connectors. They tend to produce high frequency ringing because of impedance mismatching. With a capacitive device as an electrical load, operating at high voltages, it is difficult to generate and apply a rectangularly shaped electrical pulse having fast leading and trailing edges (t_r and t_f) and obtain an optical pulse that closely reproduces the shape of the driving voltage. This is due to the impedance mismatch and the combined electrical RC time constants of the Pockels cell, cable and HV driver circuits. In spite of these limitations, these devices can be used effectively in many applications if proper care is taken with the connections and driving circuit impedance.

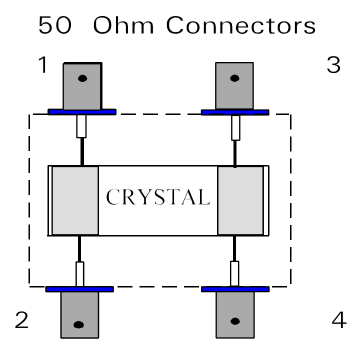
Figure 8A is perhaps the most difficult configuration to use since it is limited in the ways it can be driven. Only one electrode is accessible for applying a driving signal; the other electrode is usually common to the shell of both connectors. The device can be driven as a capacitive load, i.e., center conductor pin to signal; shell to the coaxial cable shield. The unused connector must be open but its center pin must be protected from arcing to the shell. In this way, either a pulsed voltage or static high voltage which is pulsed to zero volts can be applied to the crystal.
This device can also be used in a transmission line configuration by attaching a long length of cable to one connector and terminating this cable with its matching load impedance. The other connector receives the driving pulse. When connected in this manner, static voltages cannot be applied because of resistive loading of the driver and high power dissipation in the cable load resistor. Another driving circuit for this configuration is shown in Figure 9.



A 50 OHM CONNECTOR CONFIGURATION
CONNECTOR SHELLS AND ONE CRYSTAL ELECTRODE CONNECTED TO CASE ENCLOSURE OR SHELLS



B 50 OHM CONNECTOR CONFIGURATION
CONNECTOR SHELLS CONNECTED TOGETHER



C 50 OHM CONNECTOR CONFIGURATION
CONNECTOR SHELLS CONNECTED TOGETHER
EACH PAIR OF CONNECTORS, (1 & 2) OR (3 & 4) MAY BE DRIVEN INDEPENDENTLY OR ONE PAIR MAY BE GROUNDED TO CABLE SHIELDS & CONNECTOR SHELLS

Figure 8: Pockels Cells with 50 Ω Connectors

The circuit shown in Figure 9 can be used for Q-switching and optical pulse generation. An important aspect of this circuit is that DC voltage is blocked from the crystal. Application of static DC voltages to KD*P type crystals for long time periods causes ion migration which will eventually degrade crystal qualities. The amplitude and width of the voltage pulse applied to the crystal is a function of crystal and blocking capacitance and the combined resistances. Resistor R_L provides a ground reference and is usually in the range of 20 to 50 megohms. Actual resistance and capacitance values can be adjusted to achieve different waveform effects. The 50 Ω resistor helps suppress ringing. To maximize the pulsed voltage across the Pockels cell crystal, the blocking capacitor should be ≥20X the cell capacitance. Smaller capacitances will reduce the amplitude of the pulse and larger values will limit repetition rate.

Figure 8B is a versatile configuration since its electrodes are independent and thus can be driven as a capacitive or transmission line device. Since the electrodes are isolated, the device can be driven by a differential signal. Also, one electrode can have a bias voltage applied and the other a pulsed voltage.

Figure 8C is similar to 8B with the addition of two additional connectors. The 8C configuration has been used to generate very short optical pulses. This is accomplished by connecting the driving signal to connector #1, connecting #2 and #4 together with a short length of cable and connecting #3 to a long length of cable with a terminating resistor. The cable connection between #2 and #4 provides a time delay between application of the driving voltage pulse at #1 and then at #4. The pulse at #1 turns the modulator on and when it arrives at #4, turns it off because it is, in effect, of opposite polarity as far as the crystal is concerned.

By designing the Pockels cell to present a 50 Ω impedance to the driving circuit, rise and fall times can be minimized. The design goal for a true 50 Ohm Pockels cell is to "bury" the electro-optic crystal in a 50 Ω electrical structure so that the capacitive qualities of the crystal-electrode-structure combination are minimized. Refer to Figure 10. By choosing the appropriate, matching dielectric material, the crystal becomes part of a 50 Ω coaxial structure. The crystal capacitance is present but has a reduced effect on impedance matching. Note that this type of Pockels cell can be used as either an in-out device requiring the electrical signal to propagate through the structure as though it were part of a 50 Ω transmission line or as a capacitive device. The connector shells and part of the dielectric form a ground plane which is integral to the transmission line.

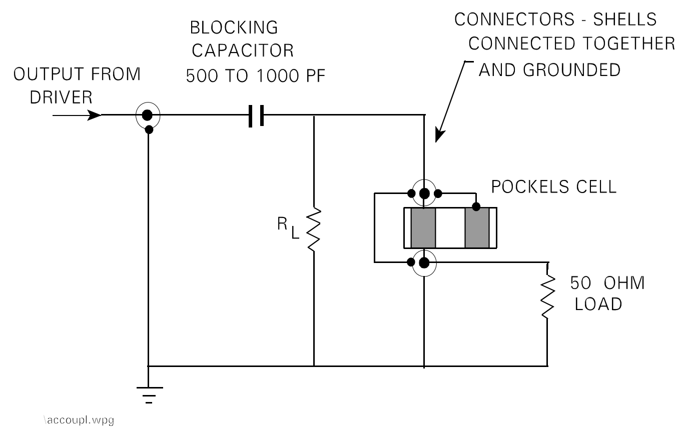


Figure 9: Circuit for blocking DC voltage from being applied to the crystal and approximating a 50 Ohm load

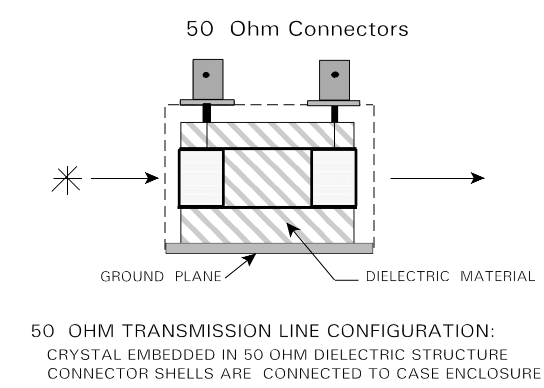


Figure 10: 50 Ohm Transmission Line Pockels Cell

Figure 11 is another form of a 50 Ω device, a representation of the Lasermetrics Model 1071, 50 Ohm Pockels cell Light Modulator. This configuration must be used as a in-out device only; the center pins of the connectors are tied together through a conductive strip which forms a strip transmission line. It cannot be used in a capacitive connection. Impedance matching in this format is excellent, and the reflection coefficient is in the range of 5%.

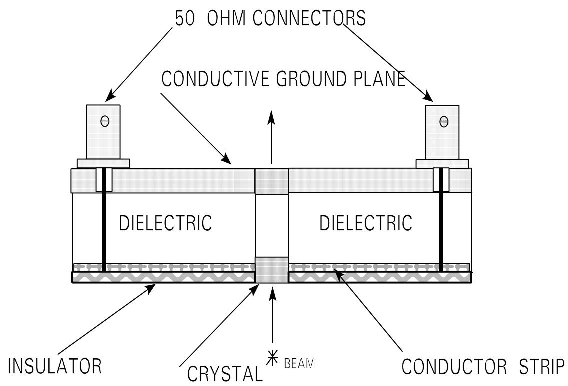


FIGURE 11: 50 OHM STRIP LINE MODULATOR

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To drive the "true" 50 Ohm Pockels cell and achieve fast rise and fall times, all the components constituting the transmission line, i.e., cables, connectors, cell and 50 Ω termination must be closely matched to 50 Ω. The length of the cable between the output connector and termination should be physically longer than the electrical pulse width. The minimum terminating cable length, in feet, required for a given pulse width in nanoseconds may be calculated as follows:

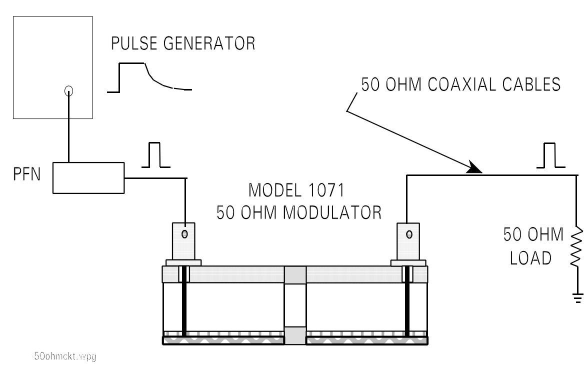
min. cable length ≈ pulse width X 1 foot/1.5 ns

A reasonable length is at least twice as long as the equivalent pulse width. The 50 Ohm termination is important in absorbing the energy in the electrical pulse after the pulse has passed the Pockels cell. A mismatch in termination impedance can result in large reflections of voltage returning from the termination to the Pockels cell. This has the effect of "opening the shutter" a second time. In some applications, where two closely spaced pulses are required, the reflected, second pulse (of theoretically equal amplitude) can be produced by removing the termination and selecting an appropriate cable length to attain the desired pulse spacing.

Driving a 50 Ω Pockels cell can present problems. This is due to the limitations of the high voltage pulse generating circuit and its ability to operate as a low impedance source in both the turn-on and turn-off modes. Further, because of power limitations on the HV switching devices, operation at high repetition rates requires expensive, high power components. The usual high voltage switching device (thyratron, avalanche transistor, MOSFET, etc.) can turn on rapidly but because of deionization time, storage time, junction capacitance and power supply considerations, the device cannot be turned off as quickly. This limitation has been largely overcome by driving the Pockels cell from a fixed, low impedance source as in Figure 12. This source is generally a pulse forming network (PFN) which is designed as a transmission line circuit.

PFNs can be constructed from coaxial cables, discreet inductive& capacitive elements or Blumlein structures. The PFN output pulse rise and fall times are dependent on the rise time of the HV switching circuit. Subnanosecond risetimes are possible with this combination of elements. Output pulse width is a function of PFN equivalent electrical length.

Many of these networks are designed as 50 Ohm systems to take advantage of available connectors and cables. To properly match the impedance of the transmission line, the Pockels cell must also be designed to present a 50 Ohm impedance to the signal pulse. Mismatched impedances result in perturbations in the electrical signal as it propagates down the transmission line. These perturbations, known as reflections, can significantly reduce the signal amplitude or result in electrical ringing which



will be expressed in the optical signal.

FIGURE 12: 50 Ω PFN DRIVER AND 50 Ω POCKELS CELL WITH MATCHED LOAD. A SERIES TYPE PFN IS SHOWN. PARALLEL PFNs ARE ALSO USED.

Another way to obtain fast optical switching is through the use of differential HV switches (FET, thyratron, transistor, etc.) which apply separate voltage pulses to first one and then the other crystal electrode. An equivalent circuit for this configuration is shown in Figure 13. The leading edge of V_{ON} forms the leading edge(t_r) of the output pulse and the leading edge of V_{OFF} forms the trailing edge (t_f) of the output pulse. Each pulse (V_{ON} & V_{OFF}) can have a fast rise time thereby generating fast rise and fall time optical pulses. Optical rise and fall times in the range of 1 to 3 nanoseconds are attainable, depending mainly on the switching elements. Pulse width is controlled by the temporal spacing between the rise times of V_{ON} and V_{OFF}. In a differential configuration, the modulator must be used in a capacitive mode. In this type of circuit, rise and fall times are sensitive to total capacitive loading and lead inductance. Therefore, wires or cables connecting to the Pockels cell must be kept very short. In fact, optimum performance is obtained by limiting the cables or connecting wires to lengths of less than one inch.

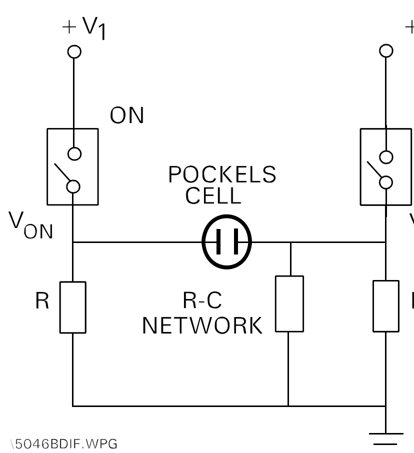


Figure 13: Differential Pulse Driver

Additional details on the differential configuration is available in Lasermetrics Application Note, "Differential Mode HV Switching Pockels Cell Driver For Laser Pulse Extraction & Gating Applications".

5.0 SOL GEL ANTIREFLECTION COATINGS

Sol Gel antireflection coatings are applied to the polished crystal faces. They provide extremely low reflectance values compared to other available means for reducing reflections from crystal faces.

Typically, sol gel AR coatings can provide a reflectance of $<0.1\%$ per surface over a relatively wide spectral band. This is particularly useful in attaining maximum power output from a Q-switched laser cavity. These coatings exhibit a very high damage threshold - equal to or exceeding the damage threshold of the crystal material (KD*P) which is typically $\approx$750 to 850 MW/cm^2 for a 10 nanosecond width Q-switched pulse and $>$20 GW/cm^2 for pulses in the femtosecond range.

The coatings will also tolerate higher average power throughput than index matching fluids. The major limitation on high average power is due to crystal absorption and subsequent changes in refractive index due to the crystal's non-isotropic characteristics.

Unlike index matching fluids, sol gel coatings do not cause "beam blooming" due to localized heating in the fluid. Nor do they exhibit non-linear refractive index effects or damage.

Sol gel antireflection coatings are optically robust but mechanically fragile. They cannot be wiped, dusted or cleaned once they are applied to a crystal surface. While most devices with sol gel coatings have AR coated fused silica protective windows, it is possible for the experienced user, who needs the highest possible transmittance, to remove the windows and operate the exposed crystal within a dust-free, low humidity, warm enclosure (such as found in many laser cavities.

Sol Gel antireflection coatings applied to the KD*P crystals have replaced index matching fluids in most of the FastPulse/Lasermetrics KD*P product line. Index matching fluid is used mainly in the UV region with wavelengths less than 35 nm and with small diameter crystals ($<$6 mm) where the sol gel coating cannot cover the surface uniformly.

5.1 ADDITION OF INDEX MATCHING FLUID TO KD*P POCKELS CELLS

Most KD*P Pockels cell Q-switches and electro-optic light modulators produced by FastPulse are equipped with a sealed housing for index matching fluid. In this type of device, the housing contains a filler hole that is sealed by compression of a Viton O-Ring with a screw. In most housings, windows may be removed for replacement or to rapidly drain the fluid. The housing may then be resealed by proper compression of the Viton O-Ring beneath the window. Removal of the protective windows is not recommended unless the user is familiar with handling water soluble crystals and the operation can be performed in a dust-free and low relative humidity (<50%) atmosphere.

It is recommended that the Q-Switch or modulator be returned to FastPulse for any operation that involves exposure of the cell interior. In cases where this is not feasible or where fluid leakage has occurred slowly over a long period, follow the filling procedure detailed below.

If it becomes necessary to add index matching fluid to the Pockels cell, a hypodermic syringe must be employed and the correct fluid type must be used. A replacement kit containing fluid, syringe, needle, and filter assembly is available from FastPulse at nominal cost.

Two kits are available: IMFK-104 and IMFK-43. Most standard production modulators and Q-switches utilize the type 43 fluid which is included with the IMFK-43 kit. Type 43 fluid has a slightly better index match than 104. The filters and filter assemblies for the 43 and 104 fluids are identical.

Another fluid in use is Decalin. Its refractive index is an almost perfect match for KDP type crystals and fused silica windows. Unfortunately it is extremely odorous, unpleasant to work with and is thought to be carcinogenic. Decalin fluid requires special filter elements and assemblies because it will chemically attack many plastics.

Decalin cannot be used in devices that were not originally designed for its use. Use of Decalin has been discontinued in FastPulse/Lasermetrics Pockels cells. If in doubt as to which index matching fluid has been used in a particular device, contact FastPulse.

A filter assembly consists of two cylindrical parts which may be unscrewed to insert the filter element. This should be done in a dry, dust-free environment. Before placing the filter assembly on the hypodermic syringe, the needle should be attached to the syringe and the syringe filled with index matching fluid. Then remove the needle, attach the filter assembly to the syringe and the needle onto the filter assembly.

Press the syringe plunger and force approximately 1 cc of fluid back into the fluid container. This will insure that any dust trapped on the output side of the filter, its housing or in the needle will not be injected into the Pockels cell. Always recap the fluid container to prevent evaporation and entry of dust particles.

The following precautions must be exercised when filling the sealed housings:

1. The interior of the sealed housing and the injected fluid must be kept free of particulate matter. A 0.22 micron Millipore filter attachment or equivalent is recommended for use with the syringe.

2. The filler hole area and screw head must be clean before the filler screw is removed. The entire operation should be performed in a dust free area.

3. When the hypodermic syringe is inserted in the filler hole, extreme care must be taken to avoid cocking the syringe and striking the crystal face. Any contact between the needle point and the crystal surface will cause a severe dig or scratch. Also avoid resting the needle point on the side of the crystal.

4. The filler screw and O-Ring must be cleaned of particulate matter before resealing. Excess index matching fluid that seeps out when the filler screw is tightened may be removed with a cloth or tissue.

5. An air bubble is left in all fluid-filled cells for pressure relief. The size of the bubble must be restricted so that it will not obstruct the optical path. Most modulators may be operated at an incline of up to 70-80 degrees with the horizontal. Such an incline is considerably less for 5/8 and 3/4 inch aperture units. When vertical operation is required, a "dry" modulator may be necessary.

6. Never return index matching fluid to its original container without injecting it through the filter. Returning it without filtering may contaminate the remaining fluid with particulate matter.