LIGO-T960210-00-D

Model Series 400X
User's Manual

DC-100 MHz Electro-Optic Phase Modulators

Post-it® Fax Note 7671

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Warranty

New Focus, Inc. guarantees its products to be free of defects for one year from the date of shipment. This is in lieu of all other guarantees, expressed or implied, and does not cover incidental or consequential loss.

Contents

Introduction

The New Focus model 400X series of electro-optic phase modulators provides an efficient means for optical phase modulation in the DC to 100 MHz frequency range. These versatile phase modulators can be operated with low to moderate drive voltages, and their 2-mm apertures make them compatible with most laser sources. Other features of these devices include their high modulation frequency, low insertion loss, good RF shielding, and high optical-power handling capability.

The model 400X series consists of four modulators classified according to operating wavelengths and electronic drive requirements. The operating wavelengths are determined by the anti-reflection coating applied to the surfaces of the electro-optic crystals. Two standard wavelength ranges are offered: 0.45-0.85 μm and 1.0-1.6 μm. Regarding electronic drive requirements, the following two types of modulators are offered:

1. **Models 4002 and 4004 Broadband Phase Modulators** can be operated at any frequency from DC to 100 MHz and require on the order of 210 volts to achieve a π phase shift.
2. **Models 4001 and 4003 Resonant Phase Modulators** operate at a single user-specified frequency anywhere in the range 0.01 to 100 MHz. These devices can only be operated at their resonant frequency but require much lower drive voltages—on the order of 16 volts to achieve a π phase shift.

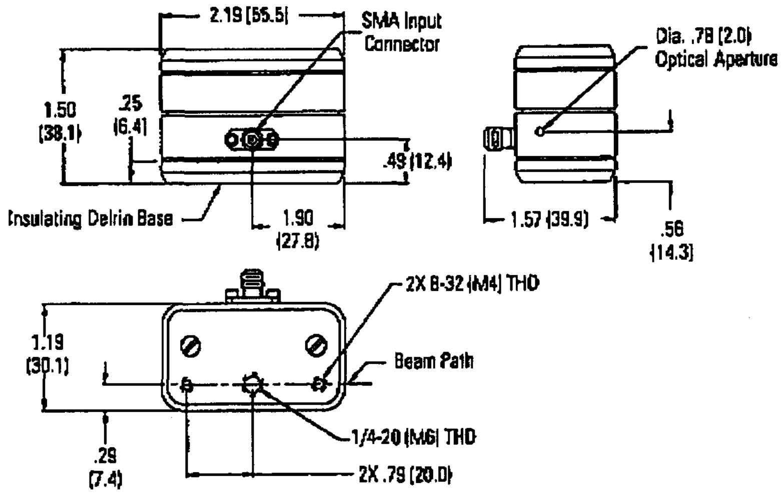
The broadband phase modulators are appropriate for applications where modulation over a broad frequency range is required. For applications requiring phase modulation at a single frequency, the resonant phase modulators are preferred because much higher phase shifts can be achieved with a given drive voltage.

All of these devices employ electro-optic crystals where an applied electric field induces a change in the crystal's refractive index. The Model 400X series phase modulators use lithium tantalate ($LiTaO_3$) and lithium niobate ($LiNbO_3$) crystals as the electro-optic medium. Magnesium-oxide-doped lithium niobate ($MgO{:}LiNbO_3$) crystals are also available for higher optical-power handling capability. All of these materials are nonhygroscopic, and so, they can be left on an optical table for indefinite periods without requiring a sealed enclosure.

Table 1 (page 15) is the product matrix for the 400X series phase modulators and lists the physical characteristics and performance specifications for these modulators. A mechanical drawing of the 400X modulator is shown in Figure 1 (page 6).

Fig. 1

Mechanical views of the model 400X electro-optic modulator.



Principles of Operation

Operation of New Focus electro-optic phase modulators is based on the linear electro-optic (or Pockels) effect —the linear dependence of the refractive index on the applied electric field. The effect of an applied electric field on a crystal's refractive index is described by a third-rank tensor r_{ij}. The induced refractive index change caused by an external electric field has the form

$$\Delta n = \frac{1}{2} n_e^3 r_{33} E,$$

where Δn is the change in the index of refraction, n_e is the unperturbed index of refraction, r_{33} is the appropriate element in the electro-optic tensor, and E is the applied electric field. $LiNbO_3$ and $LiTaO_3$ are attractive crystals for use in these types of modulators because they have wide spectral transparency windows, large r coefficients, and low RF losses.

The New Focus phase modulators consist of an electro-optic crystal of length l with electrodes separated by the crystal thickness d. The electric field is applied along a crystal axis and transverse to the direction of optical propagation. Modulation is induced onto the laser beam by aligning the polarization of the input beam with the crystal axis along which the electric field is applied. An electronic signal is then directly modulated onto the laser beam through the electro-optic effect.

For the models 4002 and 4004 broadband phase modulators, the input electronic signal is applied directly across the crystal's electrodes. So, the optical phase shift obtained by applying a voltage V at the input SMA connector is

$$\Delta\phi = \frac{2\pi}{\lambda}\left(\frac{1}{2}n_e^3 r_{33}\right)\frac{l}{d}V,$$

where λ is the free-space wavelength. A commonly used figure of merit for electro-optic modulators is the half-wave voltage, V_π, which is defined as the voltage required to produce a phase shift of 180°. Substituting into the preceding equation yields

$$V_\pi = \frac{\lambda d}{n_e^3 r_{33} l}.$$

For the broadband phase modulators, V_π is typically 210 volts at 1.06 μm, corresponding to a modulation depth, β, of 0.015 radians/volt. Note that at other wavelengths these values change proportionately. So, at 532 nm V_π is 105 volts, and β is 0.03 radians/volt.

For the models 4001 and 4003 resonant phase modulators, the crystal is combined with an inductor to form a resonant tank circuit. On resonance, the circuit looks like a resistor whose value depends on the inductor's losses. A transformer is used to match this resistance to the 50-Ω driving impedance. Putting the crystal in this resonant circuit results in a voltage across the crystal electrodes that can be more than ten times the input voltage across the SMA connector. This leads to reduced half-wave voltages and larger modulation depths when compared to the broadband modulators.

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For the resonant phase modulators, the peak phase shift obtained by applying a sinusoidal signal of average power P at the input SMA connector is

$$\Delta\phi = \frac{2\pi}{\lambda}\left(\frac{1}{2}n_e^3 r_{33}\right)\frac{l}{d}\sqrt{2PQ\sqrt{\frac{L}{C}}},$$

where Q is the quality factor of the tank circuit, L is the inductance, and C is the crystal capacitance. For the resonant phase modulators V_π is typically 16 volts at 1.06 μm, corresponding to a modulation depth β of 0.2 radians/volt.

A sinusoidal waveform applied to the modulator will produce frequency sidebands which are separated from the optical carrier by the modulation frequency. These modulation sidebands can be observed by looking at the beam with an optical spectrum analyzer. Given an induced peak optical phase shift of Δφ (in radians), the fraction of power transferred to each of the first-order sidebands is $[J_1(\Delta\phi)]^2$, where J_1 is the Bessel function of order 1. The fraction of power that remains in the carrier is $[J_0(\Delta\phi)]^2$, where J_0 is the Bessel function of order 0.

For example, imposing a sinusoidal phase shift of peak amplitude 1 radian to a cw laser beam will transfer 19% of the initial carrier power to each of the first-order sidebands and leave 59% of the power in the carrier. Note that the maximum power that can be transferred to the first-order sidebands is about 34%, and this requires a peak phase shift of 1.8 radians. For the broadband phase modulator, at 1.06 μm a 1.8 radian phase shift is achieved with about 120 volts. For the resonant phase modulator, a 1.8 radian phase shift requires an input peak voltage of about 9 volts (0.81 average power).

Operation

When used properly, the 400X series phase modulators can provide efficient phase modulation with extremely low unwanted amplitude modulation and insertion loss. The key to obtaining this pure phase modulation is good optical alignment of the beam to the crystal's propagation axis, and accurate polarization orientation of the laser's electric field with the crystal's electro-optically active axis.

To align the module to the optical beam:

1. Use the 1/4-20 (M6 for metric versions) tapped hole located on the base of the module to mount it on an adjustment-positioning device for alignment. We recommend the New Focus Model 9071 or 9071M tilt aligner because of its tilt and translation capabilities.

2. Turn on the optical beam, and orient the beam so it is vertically polarized on the input aperture (see Fig. 2). It is important to carefully align the polarization since the crystals used by New Focus are cut so that the beam propagates along the y-axis of the crystal. This orientation minimizes the effects of acoustic resonances but makes it critical that the optical beam be linearly polarized vertically along the z-axis. If the polarization of the optical beam is not properly aligned, the modulators will impose a polarization rotation as well as a phase modulation which can lead to unwanted amplitude modulation if the modulator is followed by any polarizing optics.

3. Position and align the module so that the beam passes through the 2-mm input and output apertures, clearing them without clipping. The beam

to be modulated should be collimated with a waste size of less than 2 mm, and such that the Rayleigh range is at least the length of the crystal. To avoid damage resulting from excessive optical intensity, the optical power should be kept below the damage thresholds listed in Table 1. Typically, a good beam size is 250–500 µm.

To set up the electrical modulating input signal:

Using an SMA cable, connect the SMA jack on the modulator to a modulating source appropriate for the type of modulator (resonant or broadband) you are using.

NOTE: Since the optical alignment of the modulator can be disturbed by the SMA cable, ensure that the SMA orientation is not obstructing the alignment and use a strain relief on the cable.

The models 4001 and 4003 resonant modulators are tuned to a specific frequency and require very low drive voltages, such as that from a simple crystal oscillator or a function generator that has an output impedance near 50 Ω. The reflected power from resonant phase modulators at their specified resonant frequency is very low compared to broadband modulators.

The models 4002 and 4004 broadband modulators require large drive voltages and have a bandwidth dependent on the impedance of the modulating source. With a 50-Ω source, the bandwidth will be approximately 100 MHz. The source must be able to drive an open circuit without causing damage to the source. We recommend a New Focus Model 3211 high-voltage amplifier for operation at frequencies from DC to 600 kHz.

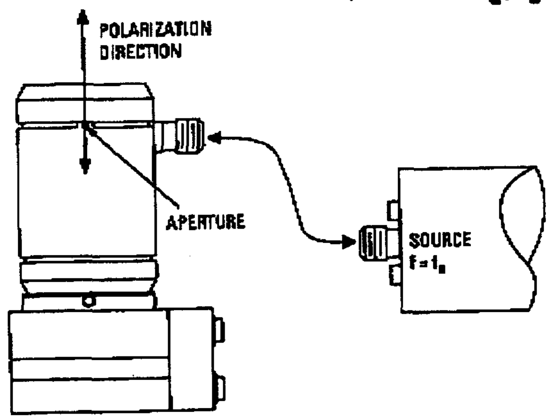

Fig. 2. A phase modulator being driven by a source tuned to f_R. The module is mounted on a Model 9071 tilt aligner. The input beam is vertically polarized.

A note about optical damage:

The electro-optic crystals used in these modulators are susceptible to optical damage through the photorefractive effect. Photorefractive damage becomes more of a problem for high optical powers, short wavelengths, and tightly focused beams. Table 1 (page 15) lists maximum average power levels above which optical damage will occur. New Focus also offers modulators with MgO-doped $LiNbO_3$ crystals which have higher damage thresholds.

The photorefractive damage process can occur gradually over days or hours, or, for high optical powers and short wavelengths, this effect can occur over seconds. A damaged crystal will distort a beam, usually by elongating it in the vertical direction. If operating close to the damage threshold, it is a good idea to monitor the transmitted beam periodically for indications of optical damage. Photorefractive damage can be partially reversed by carefully annealing the crystal; please contact New Focus for details on this procedure.

Specifications

1. Optical Throughput

Optical throughput is determined by the absorption and scatter in the electro-optic crystal, and by the quality of the anti-reflection coatings on the end faces. Low optical losses are critical in applications of the New Focus phase modulators, so great care is taken to ensure insertion loss is minimized.

2. Modulation Depth

This describes the magnitude of the phase modulation imposed on the input laser beam by the modulator. This depth is optimized by alignment of the input beam's polarization with the crystal active axis.

3. Residual Amplitude Modulation (RAM)

RAM is noise in a phase modulation system, and therefore must be minimized. Quality of crystal growth and excellence in the finished crystal design and manufacturing are essential to the elimination of RAM. Experimentally, precise alignment is required to prevent RAM from occurring.

4. Return Loss

The return loss indicates the quality of impedance matching between the driving source and a resonant phase modulator. Resonant modulators are designed to have impedances very close to 50 Ω at resonance, and a high return loss indicates a good impedance match between the driving source and the modulator. With a high return loss, power transfer to the modulator is optimized, and reflected power, which can harm RF drivers, is minimized.

The return loss indicates the fraction of RF power reflected from the modulator back to the driver when the modulator is driven at its resonant frequency. For a power reflection coefficient R, the return loss in dB is $-10 \log R$. All New Focus resonant phase modulators are tested by measuring return loss versus frequency around the modulation frequency. The results of this test are provided at the rear of this manual.

5. Voltage Standing Wave Ratio (VSWR)

VSWR, like return loss, is another way to specify the quality of impedance matching between RF driver and resonant modulator. It is defined as the voltage ratio between the maximum and minimum of the standing wave that occurs because of an impedance mismatch. A VSWR value of 1 indicates a perfectly matched system. Given a return loss RL (in dB), the VSWR can be found from

$$VSWR = \frac{1+10^{-RL/20}}{1-10^{-RL/20}}.$$

Table 1

Specifications for the 400X Series electro-optic phase modulators.

Model #	4001, 4003	4002, 4004
Wavelength	0.45–0.85 μm (4001) 1.0–1.6 μm (4003)	0.45–0.85 μm (4002) 1.0–1.6 μm (4004)
Type	Resonant PM	Broadband PM
Operating Freq.	0.01–100 MHz	DC–100 MHz
RF Bandwidth	1–2% freq.	100 MHz
Material	$LiTaO_3$ or $MgO{:}LiNbO_3$	$LiTaO_3$ or $MgO{:}LiNbO_3$
Max. Optical Power*	200 mW/mm² (633 nm) 1 W/mm² (1.3 μm)	200 mW/mm² (633 nm) 1 W/mm² (1.3 μm)
Max. Optical Power* ($MgO{:}LiNbO_3$)	5 W/mm² (647 nm)	5 W/mm² (647 nm)
Aperture	2 mm	2 mm
Optical Throughput	>93%	>93%
Residual AM†	-60 dB	-60 dB
Connector	SMA	SMA
Impedance	50 Ω	20–30 pF
Max. RF Power	1 W	-NA-
Modulation Depth (at 1.06 μm)	>0.2 rad/V	15 mrad/V
Max V_π (1.06 μm)	18 V	210 V
Return Loss	>14 dB	-NA-
VSWR	<1.5	-NA-

* In a 1 mm beam.

† RAM measured with a 1 rad phase modulation.

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Performance Data

Model Number: ____________

Serial Number: ____________

Frequency: ____________

Wavelength: ____________

Input RF Power: ____________

Return Loss: ____________

VSWR: ____________

Q: ____________

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