FPQFA Series
Piezo-Tunable Narrow Bandpass Fabry-Pérot Filters

User Guide



Table of Contents

Chapter 1 Introduction 1

1.1 Intended Use 1

1.2 Explanation of Safety Warnings 1

1.3 Description 1

1.4 Technical Data 2

1.4.1 Specifications 2

1.4.2 Mechanical Drawings 3

Chapter 2 Safety 3

Chapter 3 Installation 4

3.1 Warranty Information 4

3.2 Packing List 4

3.3 Installation Instructions 4

Chapter 4 Operation 4

4.1 General 4

4.2 Confined cavity mode 5

4.3 Mode matching 9

4.3.1 Free-space beam 9

4.3.2 Optical fiber 10

4.3.3 Alignment 11

4.4 FPQFA Filter Mounting 13

4.5 Driving Electronics 14

Chapter 5 Maintenance and Cleaning 16

Chapter 6 Troubleshooting and Repair 16

Chapter 7 Disposal 16

Chapter 8 Thorlabs Worldwide Contacts 17

Chapter 1 Introduction

1.1 Intended Use

These products are intended to be used as narrow optical filters in low-power applications, where the resonant transmission frequency is controlled by an external piezo controller. Depending on the application and operational wavelength, the piezo controller can be an integrated signal generator and amplifier, such as the SA201B Control Box for Scanning Fabry-Pérot Interferometers, or a PID controller, such as the DSC1 Compact Digital Servo Controller, in combination with a high voltage amplifier, such as the MDT694B Open-Loop Piezo Controller or the BPA100 High-Voltage Piezo Amplifier.

The products may only be used in accordance with the instructions described in this manual. Any other use will invalidate the warranty.

1.2 Explanation of Safety Warnings

NOTICE Indicates information considered important, but not hazard-related, such as possible damage to the product.


Laser Radiation Warning


Shock Warning


The symbol on the product, the accessories or packaging indicates that this device must not be treated as unsorted municipal waste but must be collected separately

1.3 Description

The FPQFA filters are narrow tunable optical Fabry-Pérot filters with high transmission and large Free Spectral Range (FSR) used to examine the spectral fine-structure characteristics, especially for low light emitters. Due to the carefully designed cavity with high transmission and high extinction, the FPQFA filters are suitable to be used in a feedback loop to lock the transmission at a specific wavelength and reject other wavelengths including an optical pump beam.

The optical filters are based on a non-confocal cavity consisting of two high reflectivity mirrors, one planar and one spherical. By varying the mirror separation with a piezoelectric transducer, the cavity acts as a very narrow tunable optical bandpass filter. Knowing the FSR of an FPQFA filter allows the time-base of an oscilloscope to be calibrated to facilitate quantitative measurements of a spectrum. With a transmission of more than 80%, a 30 GHz FSR, and a resolution of better than 100 MHz, the emission spectra from low-light quantum emitters, such as InGaAs quantum dots or Si and N vacancies in diamonds, can be studied efficiently.

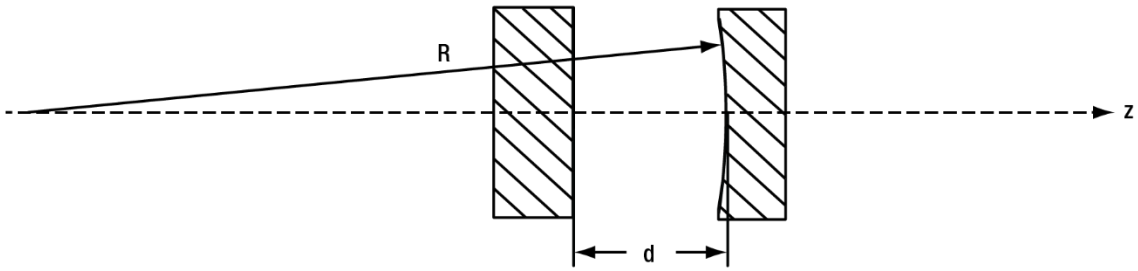


Figure 1 Illustration of the non-confocal plano-concave cavity, where the spherical mirror radius of curvature, R, is larger than the mirror spacing, d.

The non-confocal cavity in the FPQFA filters differs from the confocal cavity in the Thorlabs' SA series of scanning Fabry-Pérot interferometers. In the latter, both mirrors are spherical with the same radius, which is also equal to the mirror separation. In the FPQFA filters, the cavity consists of one planar and one concave spherical mirror where the mirror radius is significantly larger than the mirror separation, see R and d in Figure 1.

The benefit of a plano-concave cavity is that it is easier to achieve high performance at a large FSR, i.e., smaller mirror distances, than with a confocal cavity, while still having better spatial mode control than in a cavity with planar mirrors (plano-plano cavity). A drawback is that the alignment of the cavity is slightly more sensitive than the confocal cavity, but less sensitive than the plano-plano cavity.

From a user's perspective, the free spectral range of a non-confocal cavity is given by:

$$FSR = c/2d\ ,$$

where *c* is the speed of light and *d* is the cavity length. N.B. the factor 2 in the denominator as for a plano-plano cavity instead of a factor 4 as in a confocal cavity such as the Thorlabs' SA series of scanning Fabry-Pérot interferometers.

1.4 Technical Data

1.4.1 Specifications

Item #	FPQFA-5	FPQFA-8	FPQFA-13
Wavelength Range	550 – 845 nm	845 – 1300 nm	1270 – 2000 nm
Mirror Substrate	UV Fused Silica		Infrasil®[a] 302
Free Spectral Range	30 GHz		
Finesse	>300		
Resolution	<100 MHz		
On-Resonance Transmission	>80 %		
Extinction (Excluding Higher Order Modes)	30 dB (Typ.)		
Cavity Length	5 mm		
Piezoelectric Transducer Voltage	0 to 150 V		
Voltage 1 FSR, Typical (Voltage < 50 V, 550 ≤ λ ≤ 2000 nm)	4 + 0.016*λ V		
Electric Impedance	2.2 µF		

a. Infrasil is a registered trademark of Heraeus Quarzglas.

1.4.2 Mechanical Drawings

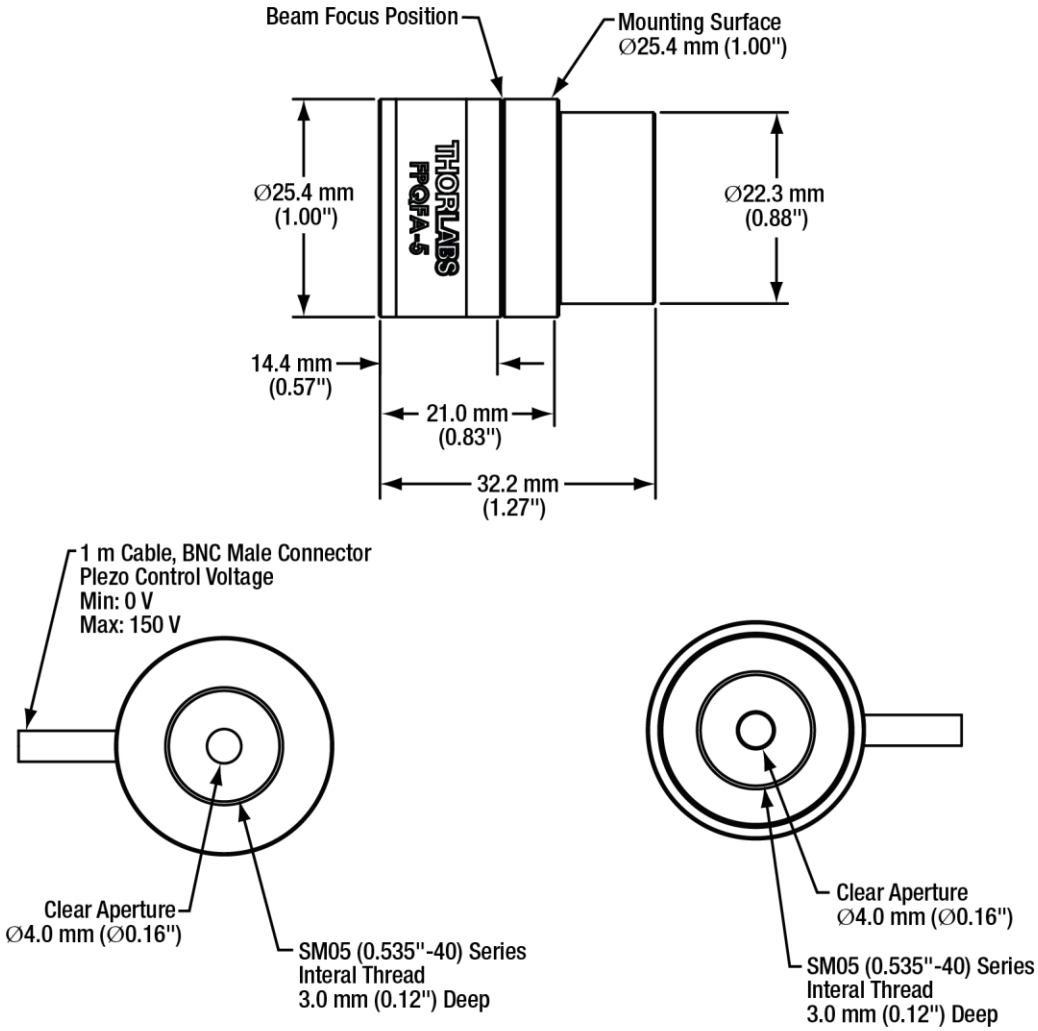


Figure 2 Mechanical Drawing for FPQFA-5, FPQFA-8 and FPQFA-13

Chapter 2 Safety

Warning
Take appropriate measures for eye safety. Never look directly into the laser beam, not even at the output of the FPQFA filters.

Risk of Electric Shock
Never touch the output of the piezoelectric driver.

NOTICE Never apply voltages below 0 V or above 150 V as it may damage the FPQFA filters.

Chapter 3 Installation

3.1 Warranty Information

This precision device is only serviceable if returned and properly packed into the complete original packaging including the complete shipment plus the cardboard insert that holds the enclosed devices. If necessary, ask for replacement packaging. Refer servicing to qualified personnel.

3.2 Packing List

- FPQFA Tunable Narrow Bandwidth Fabry-Pérot Filter
- 2 SM05CP2 End Caps

3.3 Installation Instructions

1. Depending on the application, insert the device in a fixed or kinematic mirror mount for Ø1" optics.
2. Remove the end caps.
3. Connect the piezo cable to the driving electronics before turning it on.
4. Follow the alignment instruction in Chapter 4.

Chapter 4 Operation

Warning
Take appropriate measures for eye safety. Never look directly into the laser beam, not even at the output of the FPQFA filters.

4.1 General

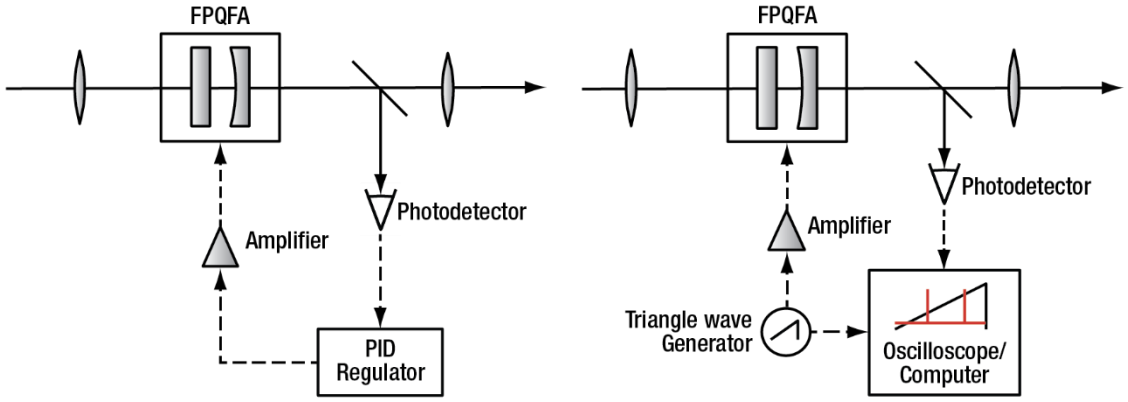


Figure 3 The FPQFA filters used in two different applications: (Left) As a frequency selective filter in a closed-loop feedback system. (Right) As a frequency scanning filter to examine the light's spectral properties.

The FPQFA Tunable Narrow Bandpass Fabry-Pérot Filters can be used in two major modes of operation, see Figure 3 (Left) and (Right):

1. As an electrically tunable optical filter selecting a part of the incoming light's spectrum given by the filter's Gaussian-shaped transmittance characteristics. In this case, the spectrally filtered light is collected by the down-stream optics for further use.

2. As a frequency scanning filter in combination with a detector to measure the spectral structures of the incoming light.

Irrespectively of which application the FPQFA filters will be used in, it is very important to properly shape the illuminating light beam to match the fundamental mode supported by the cavity. This is also known as mode-matching and will be discussed in the following sections.

4.2 Confined cavity mode

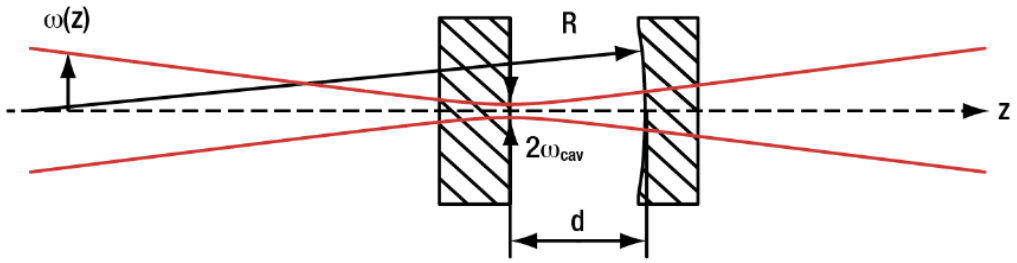


Figure 4 A plano-concave cavity, illuminated with a mode matching the cavity fundamental mode.

The plano-concave cavity supports a fundamental mode whose waist is on the flat mirror, with a Gaussian intensity profile:

$$I(r) = e^{-2\left(\frac{r}{\omega_{cav}}\right)^2},$$

where the spot size ω_{cav} is determined by the cavity length d and the radius of curvature of the curved mirror R as:

$$\omega_{cav} = \sqrt{\frac{\lambda}{\pi}\sqrt{d(R-d)}}\ .$$

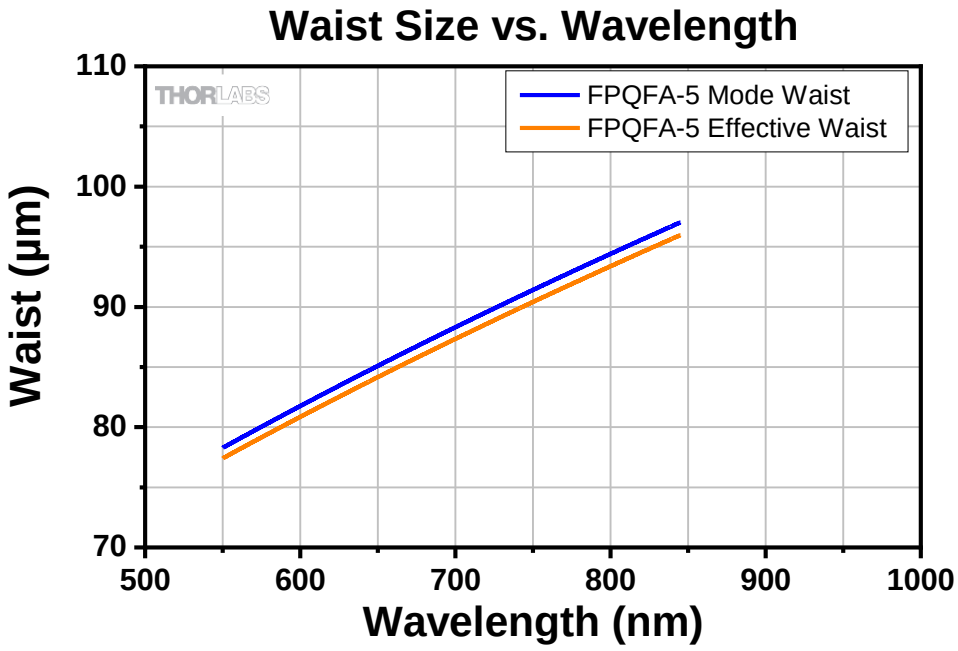


Figure 5 ***Fundamental cavity mode and effective waist size for the FPQFA-5 filter versus wavelength.***

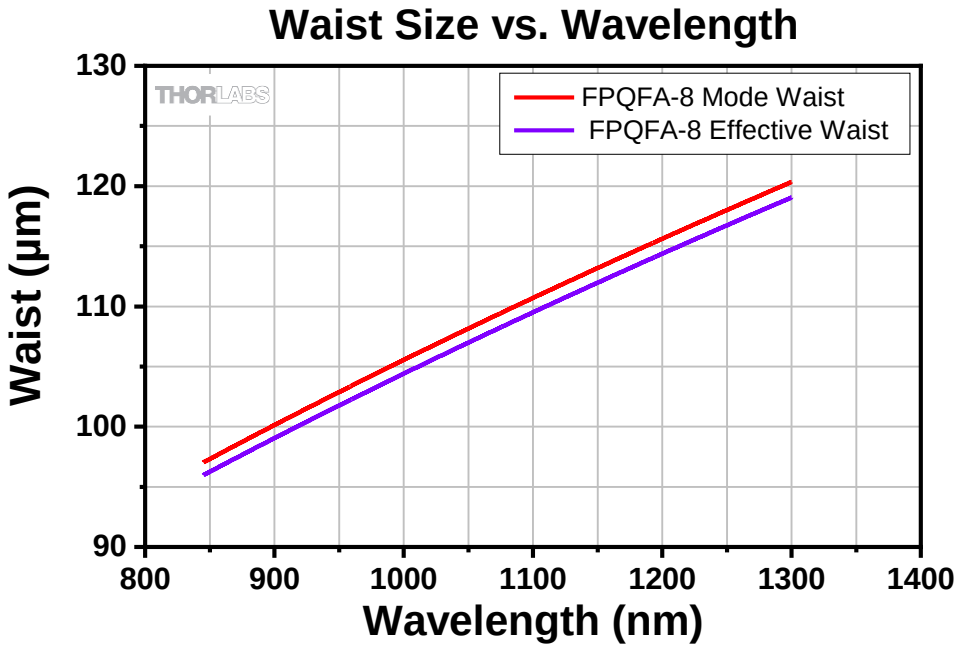


Figure 6 ***Fundamental cavity mode and effective waist size for the FPQFA-8 filter versus wavelength.***

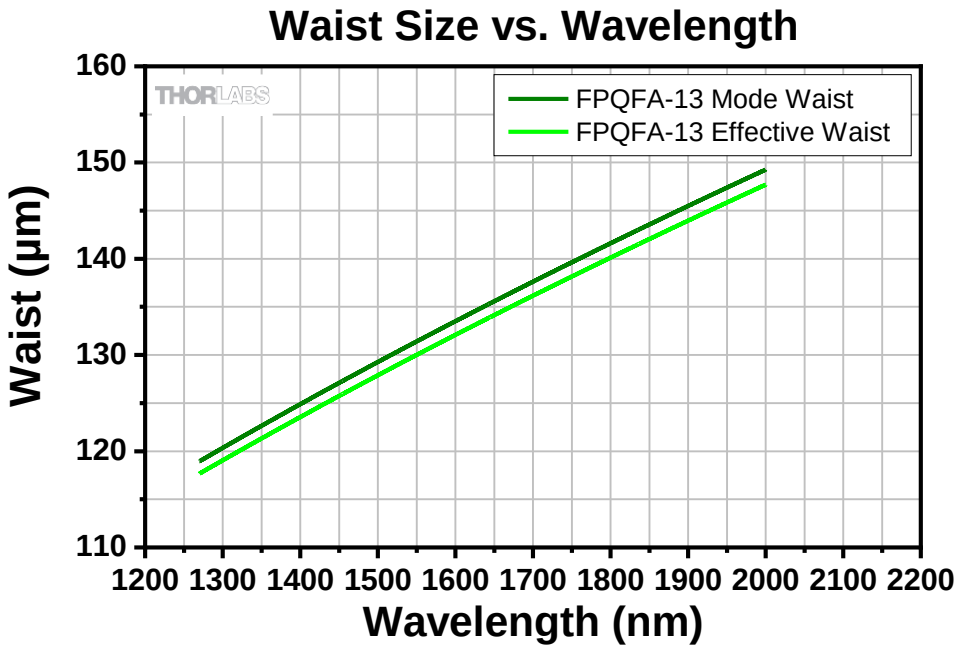


Figure 7 ***Fundamental cavity mode and effective waist size for the FPQFA-13 filter versus wavelength.***

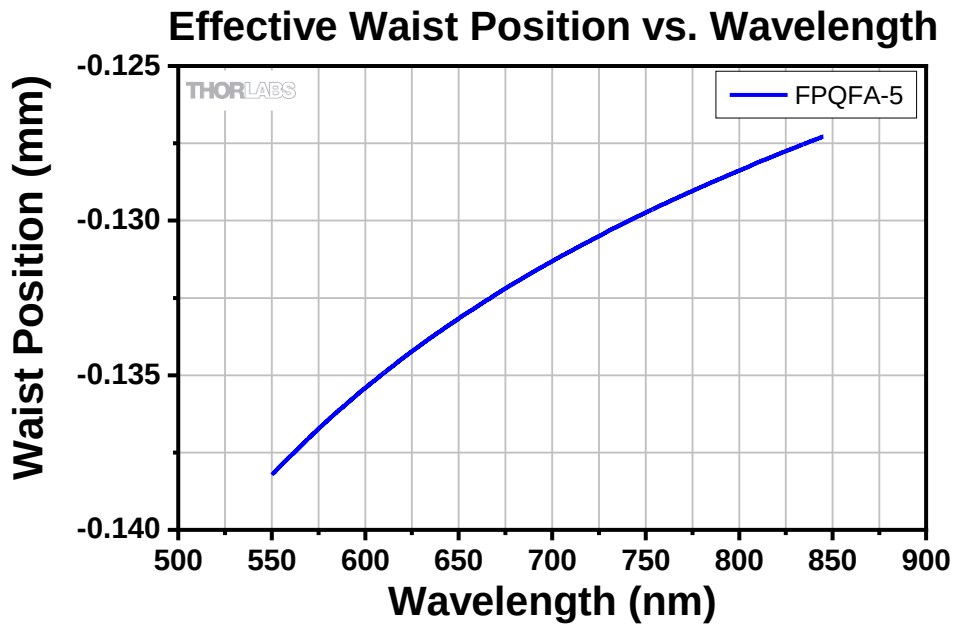


Figure 8 ***Effective waist position for the FPQFA-5 filter versus wavelength.***

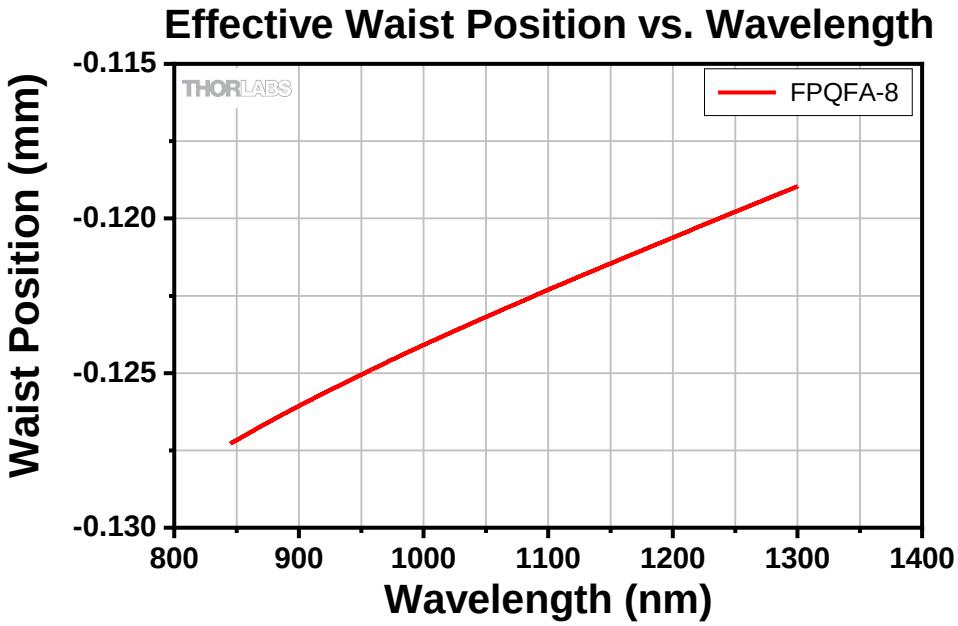


Figure 9 ***Effective waist position for the FPQFA-8 filter versus wavelength.***

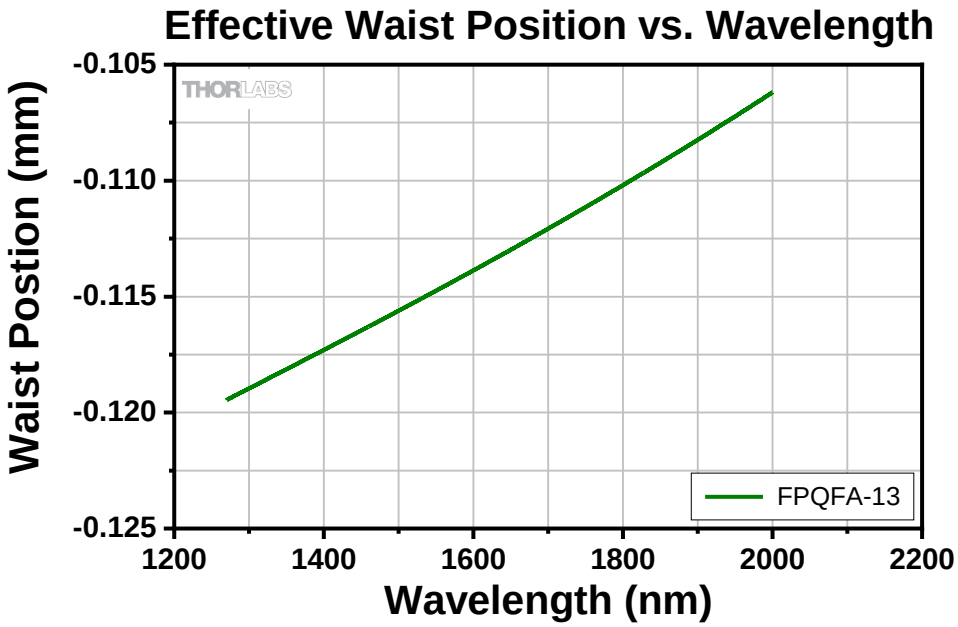


Figure 10 ***Effective waist position for the FPQFA-13 filter versus wavelength.***

For the cavity of the FPQFA filters, d = 5 mm, and R = 250 mm. The value of ω_{cav} depends on the wavelength, with representative values plotted in Figure 5.

If the light transmitted by the cavity should be collected by downstream optics, it is important to consider the impact of the planar last surface. This planar surface will slightly affect the waist size and waist position as seen after the device in Figure 4. This effective waist size for FPQFA-5, FPQFA-8, and FPQFA-13 filters is also plotted in Figure 5, Figure 6, and Figure 7, respectively. Figure 8, Figure 9, and Figure 10 show the position relative to the actual waist position (coinciding with the flat mirror) for FQFA-5, FPQFA-8, and FPQFA-13 filters, respectively. A negative effective waist position means that the effective waist is located before the real waist position in Figure 4.

It is important to recognize that the geometry of this confined cavity mode is completely determined by the cavity and the wavelength, independently of the light incident upon the cavity. In practice, we wish to "mode-match" the incoming light to the cavity by shaping the ingoing light to have the same spot size at the waist, position the waist of the ingoing light at the same position as the waist of the cavity mode, and orienting the ingoing light in the same direction as the cavity mode.

4.3 Mode matching

The two most common situations that arise are that of a free-space incident beam, and that of light emerging directly from an optical fiber. We will treat both cases.

4.3.1 Free-space beam

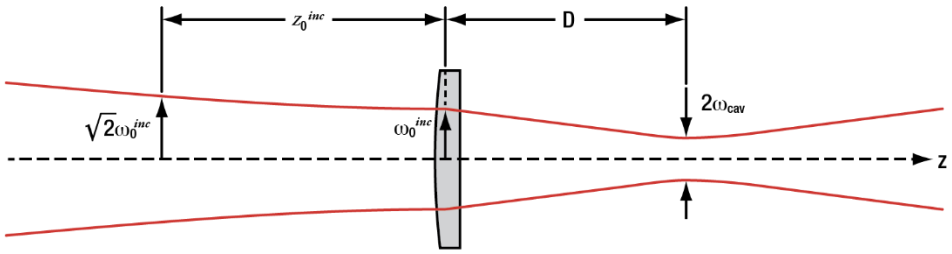


Figure 11 A Gaussian beam is focused by a lens with focal length f a distance D from the lens.

In most cases the incident beam has a Gaussian profile with intensity distribution

$$I(r) = e^{-2\left(\frac{r}{\omega_0}\right)^2}.$$

Note that ω_0 is the radius at which the intensity has dropped from the on-axis intensity by a factor of $1/e^2$; 86 % of the optical power is contained within this radius. It is conventional to refer to ω_0 as the "radius" of the beam and $2\omega_0$ as its "diameter". It is straightforward to measure ω_0 with a knife edge, a beam profiler, or a CMOS camera. After propagation through the lens with focal length f, the light is focused to a spot size

$$\omega_1 = \frac{\lambda f}{\pi\omega_0\sqrt{1+\left(\frac{f}{z_0}\right)^2}}$$

at a distance

$$D = \frac{f}{1+\left(\frac{f}{z_0}\right)^2}$$

from the lens, as shown in Figure 11. The equations tell us that a lens with smaller focal length f will focus a beam more tightly. The parameter z_0 is called the Rayleigh range and is the distance at which the spot size of the beam has increased a factor of $\sqrt{2}$ from the waist size. It is calculated as

$$z_0 = \frac{\pi\omega_0^2}{\lambda}.$$

For $z_0 \gg f$, the expression for the spot size reduces to

$$\omega_1 = \frac{\lambda f}{\pi\omega_0}$$

and the distance to

$$D = f\,.$$

In order to mode-match from a collimated beam of radius ω_0 to a cavity mode spot size ω_{cav}, one should use a lens with focal length

$$f = \frac{\pi\omega_0\omega_{cav}}{\lambda}\,.$$

For example, a collimated beam from a TC06 Triplet Fiber Optic Collimator entering the lens with radius ω_0 = 0.56 mm and requiring a focused spot size of ω_{cav} = 84 µm at λ = 633 nm, gives a focal length of f = 233 mm. To mode-match an incident beam of the same radius ω_0 to a cavity mode radius ω_{cav} = 120 µm at λ = 1300 nm, a focal length of f = 162 mm is needed. Lenses with focal lengths of f = 250 mm in the first case, and f = 150 mm or 175 mm in the latter example would be reasonable choices. In practice, the incident beam radius ω_0 is usually not known precisely, and satisfactory results will be obtained with a focal length in the vicinity of the calculated value. For best results, it is recommended to verify the waist spot size and position by measurement as described earlier. If the setup cannot accommodate the lens due to space constraints, increasing the incident beam waist ω_0 will also increase the required focal length.

4.3.2 Optical fiber

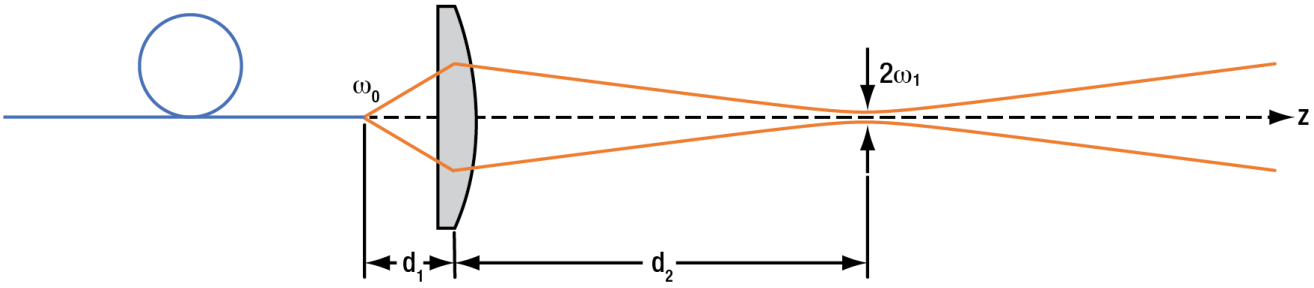


Figure 12 Mode-matching from an optical fiber.

The other situation that occurs frequently is that the light to be injected into the cavity emerges from a single-mode fiber. In this case an adjustable fiber collimator, such as Thorlabs CFC5A or PAF2-7A, can shape the optical mode to the desired shape. The light emerges from the fiber with a spot size given by

$$\omega_0 = \frac{\lambda}{\pi\theta}\,,$$

where θ is the numerical aperture of the fiber (typically around θ = 0.13). As an example, for fiber 780HP with θ = 0.13 at a wavelength of 845 nm, one finds ω_0 = 2.06 µm. Note that this is slightly smaller than half of the mode field diameter of 5.0 ± 0.5 µm specified for this fiber.

If the distance d_1 from the fiber tip to the lens in the collimator is

$$d_1 = f\left(1 + \frac{\omega_0}{\omega_1}\right),$$

The light emerging from the collimator will be refocused to a spot a spot size ω_1 at a distance

$$d_2 = f\left(1 + \frac{\omega_1}{\omega_0}\right)$$

from the lens, as shown in Figure 12. In practice, one chooses a collimator with a focal length that will give a convenient distance d_2 to the cavity. For example, with ω_0 = 2.07 µm and $\omega_1 = \omega_{cav}$ = 97 µm, one finds

$$d_1 = 1.02f$$
$$d_2 = 48f\ .$$

A collimator with a focal length of f = 4.6 mm, such as Thorlabs CFC5A, would give d_1 = 4.69 mm and d_2 = 221 mm. In a real setup, one would adjust the collimator (and thus d_1) to get the desired waist size and position of the emerging beam.

4.3.3 Alignment

After selecting the proper lens according to the previous section, it is necessary to have enough degrees of freedom in the alignment setup to adjust the incoming focused beam to achieve proper mode-matching. There are several possible solutions to achieve the necessary degrees of freedom, two of which are presented here.

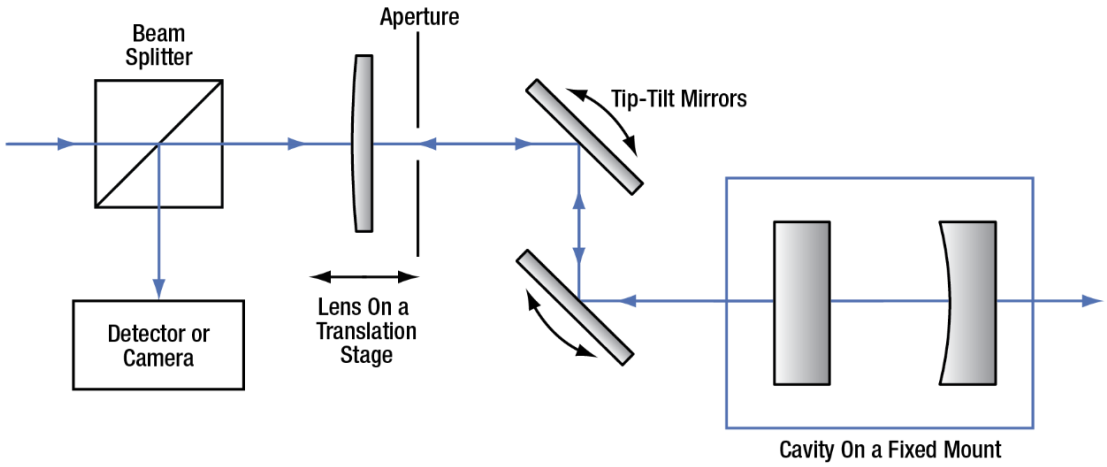


Figure 13 Example of an alignment setup with the five degrees of freedom necessary for mode-matching (only three degrees of freedom are shown in the figure), where an FPQFA filter is used as a tunable optical filter.

Correct mode-matching requires spatially overlapping the injected light with the fundamental mode of the cavity. This requires five degrees of freedom, three for translation (x, y, and z) and two for angular alignment (around x- and y-axes).

Figure 13 illustrates a setup where the cavity is fixed, and the incident beam is shaped to match the cavity mode and aligned to the cavity. This setup is suitable when the light transmitted through the cavity is collected by downstream optics for further processing since the direction of that light is set by the cavity and hence fixed. Two steering mirrors provide control of the position and angle of the incoming beam, and the axial position of the waist is controlled by moving the focusing lens. Of all the degrees of freedom, the axial position (z) is the least critical. A characteristic length scale for it is provided by the distance

$$z_{cav} = \sqrt{d(R-d)} = 35mm$$

at which the spot size of the confined mode increases due to diffraction by a factor of $\sqrt{2}$, indicating that the axial position needs to be correct to only a few millimeters. This distance is also known as the Rayleigh range.

If space permits, an optional beam splitter can be helpful in establishing the correct lens position. When the waist is correctly positioned on the flat mirror of the cavity, the reflected beam will be collimated, which can be evaluated by looking at the reflection from the beam splitter.

Also, an aperture placed before to the steering mirrors can help to ensure that the incident beam is perpendicular to the flat cavity mirror. Aligning the mirrors such that light reflected by the cavity passes back through the

aperture ensures that the injected beam is perpendicular to the cavity input coupling mirror. In a fiber system, the same goals may be achieved by using a circulator and optimizing the reflected power.

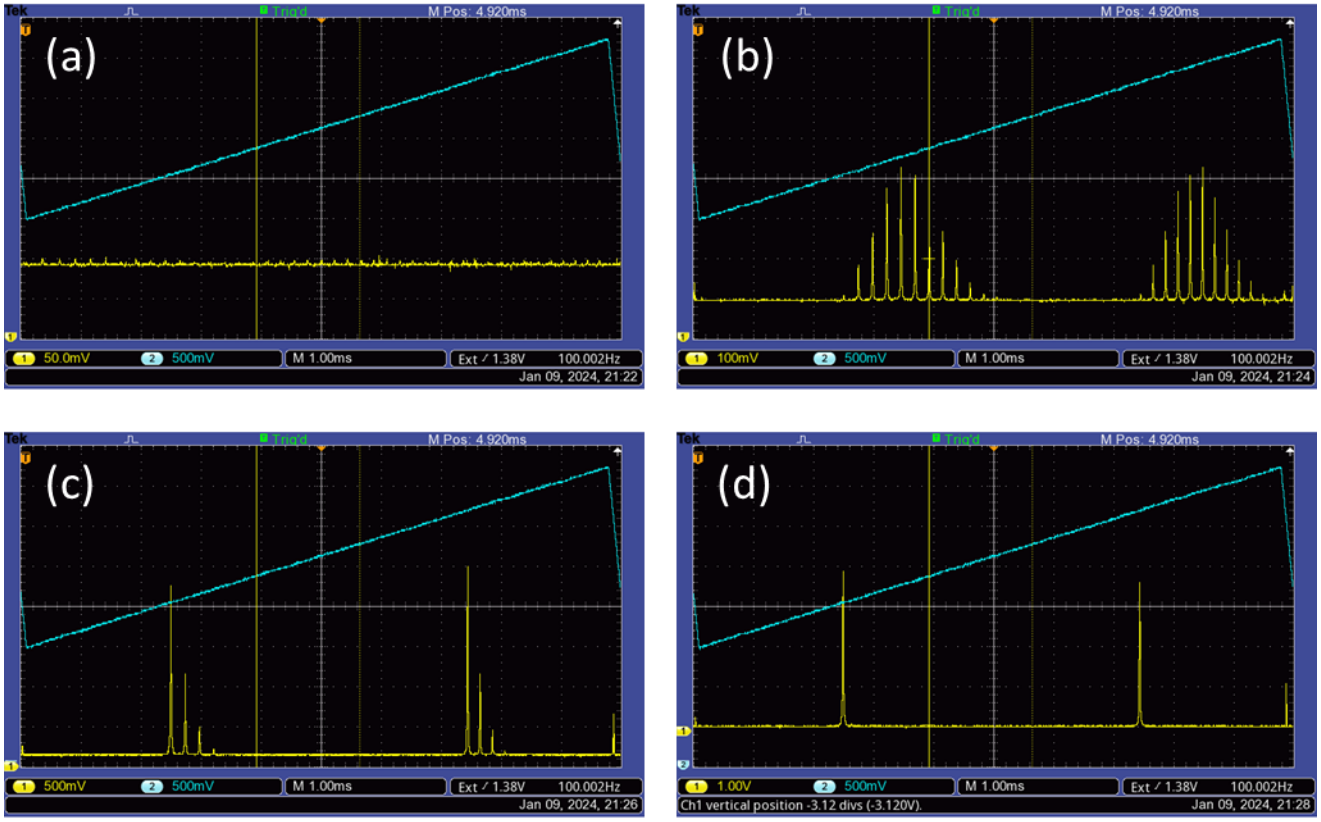


Figure 14 Oscilloscope signal (a) after initial rough alignment, (b) after first iteration, (c) after second iteration, (d) when mode-matching is achieved. Note the different voltage scale in the figures.

After this first rough alignment, when placing a detector after the cavity and displaying the signal on an oscilloscope, one can expect to see a transmission signal as the cavity length is scanned with the piezoelectric actuator, see Figure 14a. To optimize the alignment of the two steering mirrors, the suggested procedure is as follows:

- With the mirror furthest from the cavity, turn the knob controlling the horizontal motion a small amount in the clockwise direction, then optimize the transmitted power with the knob controlling the horizontal motion on the other mirror.
- If the transmission is better than where it started, return to the first mirror, and turn the knob again in the clockwise direction and repeat.
- If the transmission is worse than where it started, turn the knob on the first mirror in the counterclockwise direction and repeat.
- Continue the process until the horizontal degree of freedom is optimized.
- Repeat the procedure in the vertical motion.
- Iterate optimizing the horizontal and vertical motion as necessary until the best transmission is found.

At this point, there should be very little power coupling into higher order modes (Figure 14d). If the mode-matching is still not satisfactory, it may be necessary to translate the lens axially or change the focal length.

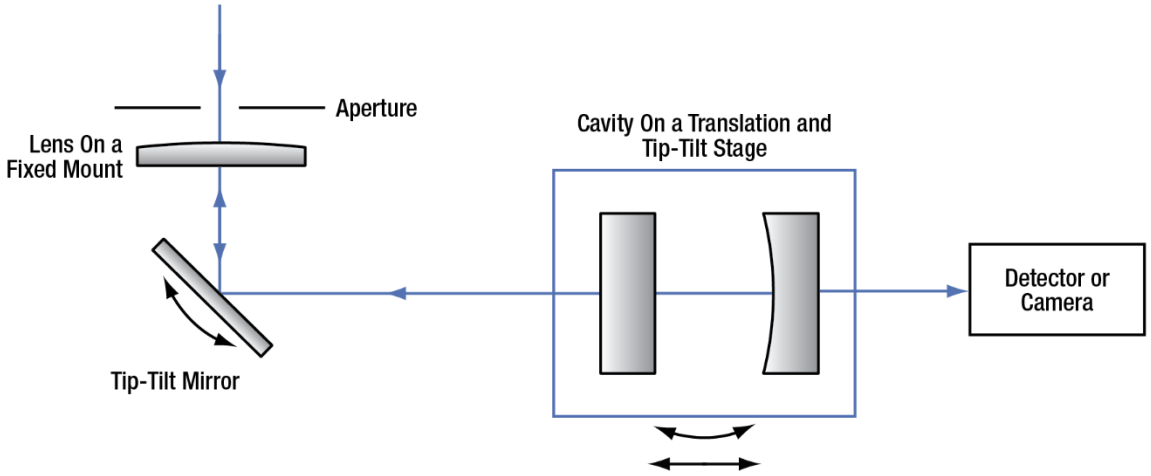


Figure 15 Example of an alignment setup with the five degrees of freedom necessary for mode-matching (only three degrees of freedom is shown in the figure), where an FPQFA filter is used as a frequency scanning filter.

There are many alternatives to the setup illustrated in Figure 13 in which the cavity is fixed, and two steering mirrors are used for alignment. One popular scheme has the cavity itself in a kinematic mirror mount (we recommend the Polaris-K1E or KS1 mount), providing two degrees of freedom, in which case only one steering mirror is needed to provide two more degrees of freedom, see Figure 15.

This setup has the benefit of easier alignment compared to the previous example, since there is less coupling between beam angular and position alignment. The steering mirror mainly affects the horizontal and vertical spot position in the cavity and the cavity tip-tilt mainly affects the injected beam's direction in the cavity. The drawback is that the transmitted beam after the cavity will change direction during the alignment. Hence, this setup is best suitable when a detector or camera is placed directly after the cavity.

4.4 FPQFA Filter Mounting

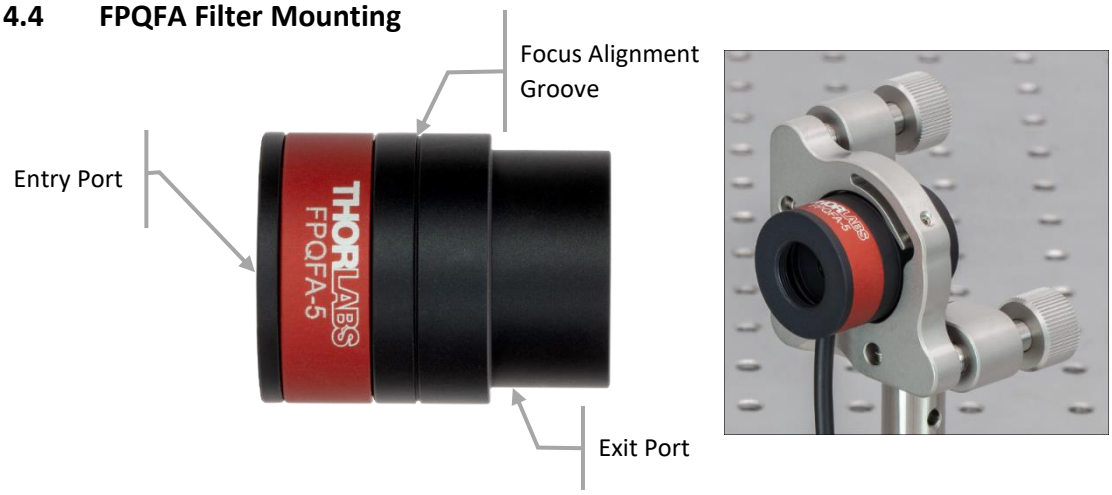


Figure 16 (Left) Entry and exit port and focus alignment groove on housing indicating the focus position. (Right) FPQFA-5 filter mounted in a POLARIS-K1E mirror mount.

When mounting the FPQFA filters in a setup, it is recommended that the incoming light enters the device through the entry port located on the side marked with the red ring, see Figure 16 (Left). Also, the axial focus position of the shaped incoming beam should coincide with the focus alignment groove on the housing. This groove is aligned with the internal planar cavity mirror. To facilitate alignment for the user, when the FPQFA filters are mounted in a Thorlabs mirror holder for Ø1" optics (such as the Polaris-K1E or KS1), the focus alignment groove coincides with the mirror holder front face, see Figure 16 (Right).

If needed, the FPQFA filters can also be operated in reverse with the incoming light entering the device through the exit port, if the focus position is aligned to the focus alignment groove.

4.5 Driving Electronics



Risk of Electric Shock
Never touch the output of the piezoelectric driver.

NOTICE Never apply voltages below 0 V or above 150 V as it may damage the FPQFA filter.

Depending on the mode of operation, the requirements on the electronics used to drive the FPQFA tunable optical filters are different. If the FPQFA filters are used in a closed feedback loop, the drive electronics must be able to generate the voltage and current to follow the PID correction signal. In case the FPQFA filters are used as a frequency scanning device, the drive electronics need to be able to generate a sawtooth or triangle wave of high enough voltage and current to drive the capacitive load.

Note that the driving electronics should be able to generate at least twice the voltage required for 1 FSR to guarantee that two resonant transmission peaks can be resolved. If the wavelength of the laser source can be tuned to move the peaks, the required output voltage can be lowered to 1.5 FSR. The Thorlabs SA201B control box, with a maximum output voltage of 45 V, can be used for wavelengths < 1150 nm, if the output voltage is taken to be 2 FSR, and < 1620 nm, if the output voltage is taken to be 1.5 FSR, respectively.

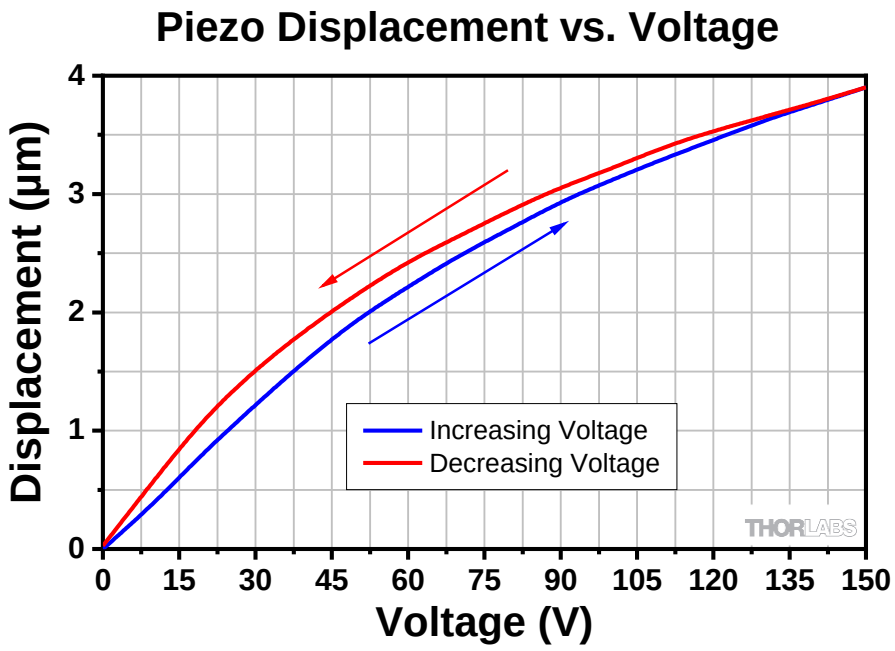


Figure 17 Piezoelectric actuator displacement without load versus applied voltage for increasing and decreasing voltage.

Common to all piezoelectrical actuators is that they are non-linear and exhibit hysteresis, including the actuator used in the FPQFA filters. The typical displacement of the piezoelectrical actuator when applying a static voltage across it is displayed in Figure 17. As the displacement is not linear with the applied voltage, the required voltage to scan the filters 1 FSR (a distance $\lambda/2$) is not only wavelength-dependent, but also applied voltage-dependent. Since the displacement per Volt decreases with increasing voltage, the required voltage increases with increasing voltage. An expression for a rough estimate of the required voltage for 1 FSR at voltages below 50 V is

$$V_{1FSR} \leq 4 + 0.016 * \lambda,$$

where λ is the wavelength in nm.

The maximum current requirement when applying a time-varying voltage over a capacitive load is:

$$I_{max} = C \frac{dV(t)}{dt}_{max},$$

where C is the capacitance of the piezoelectric element and $dV(t)/dt_{max}$ is the maximum slope of the signal (slew rate).

If the FPQFA filters are used in a high-speed closed-loop control system, the current requirement will depend on the characteristics of the control system, such as bandwidth, latency, etc. Depending on the requirements, an amplifier with higher output current, such as the BPA100, may be required.

An expression for the maximum current requirement when applying a sinusoidal signal is:

$$I_{max} = \pi f C V_{pp},$$

where f is the frequency, C is the piezoelectric actuator capacitance, and V_{pp} is the peak-to-peak voltage.

When applying a triangular wave with the SA201B control box for Scanning Fabry-Pérot Interferometers (maximum output current 25 mA), the maximum voltage slope is 11 V/ms, which can be sufficient for applications when the FPQFA filters are used as a frequency scanning device.

Chapter 5 Maintenance and Cleaning

There are no user serviceable parts in the FPQFA filters, and the device should only be sent back to Thorlabs for fault analysis and repair after consultation with Thorlabs personnel.

If needed, the outside of the FPQFA filters housing can be cleaned with a damp lint free cloth. Make sure not to let any water enter the entry and exit ports.

The backside of the mirrors, which is visible through the entry and exit ports, can only be cleaned with clean compressed air. Never touch the backside of the mirrors with any physical objects.

Chapter 6 Troubleshooting and Repair

Below are a few checks to help in troubleshooting problems that may arise. Please contact your local Thorlabs Technical Support office with any questions.

Problem	Suggested Solutions
There is no transmission signal on the oscilloscope.	Verify that the FPQFA filter is connected to the driving electronics.
	Verify that the driving electronics is on and generating the right output.
	Verify that the transmitted or reflected beam is not obstructed and hits the detector properly.
	Slightly move the beam in the horizontal and vertical direction with the first steering mirror until a signal as in Figure 14(a) is achieved.
	Increase the voltage scan range to make sure the frequency scan is at least 1 – 2 FSR's, see FPQFA filter Specifications Table in Section 1.4.1.
	Verify that the cable is still soldered to the piezoelectrical actuator by applying a 100 Hz 10 V sawtooth wave and listen for a "buzzing" sound.

Chapter 7 Disposal



Thorlabs verifies our compliance with the WEEE (Waste Electrical and Electronic Equipment) directive of the European Community and the corresponding national laws. Accordingly, all end users in the EC may return "end of life" Annex I category electrical and electronic equipment sold after August 13, 2005 to Thorlabs, without incurring disposal charges. Eligible units are marked with the crossed out "wheelie bin" logo (see right), were sold to and are currently owned by a company or institute within the EC and are not dissembled or contaminated. Contact Thorlabs for more information. Waste treatment is your own responsibility. "End of life" units must be returned to Thorlabs or handed to a company specializing in waste recovery. Do not dispose of the unit in a litter bin or at a public waste disposal site. It is the user's responsibility to delete all private data stored on the device prior to disposal.

Chapter 8 Thorlabs Worldwide Contacts

For technical support or sales inquiries, please visit us at www.thorlabs.com/contact for our most up-to-date contact information.



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