FPQSA Series
Temperature-Controlled Narrow Bandpass Fabry-Pérot Filter

User Guide



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Chapter 1 Introduction

1.1 Intended Use

This product is intended to be used as a narrow optical filter in low power applications, where the resonant transmission frequency is set and controlled by a separate temperature controller such as the TC300B Heater and TEC Temperature Controller.

The product 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


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 FPQSA is a temperature-controlled narrow optical Fabry-Pérot filter with high transmission, large Free Spectral Range (FSR), and high extinction ratio used to effectively filter an incoming light beam. Due to the thermally stable design, the resonant transmission of the FPQSA can easily be positioned at one frequency and effectively reject other frequencies without the need for any expensive and complicated laser locking electronics to lock the resonant transmission at a specific wavelength.

The optical filter is based on a monolithic non-confocal etalon consisting of two high-reflectivity mirrors, one planar and one spherical, see Figure 1. By tuning the temperature of the etalon, both the physical thickness and the refractive index of the Infrasil®† 302 substrate will change accordingly, thereby affecting the optical path length of the etalon and the resonant transmission frequency.

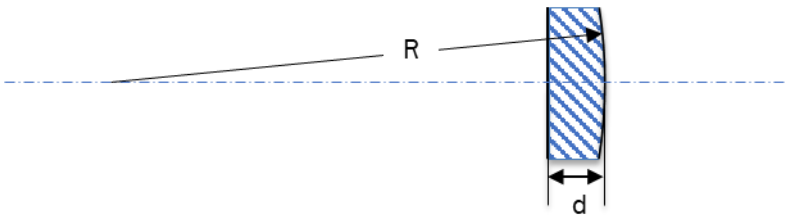


Figure 1 Illustration of the non-confocal plano-concave monolithic etalon where the spherical mirror radius of curvature, R, is larger than the mirror spacing, d.

The non-confocal etalon in the FPQSA is similar to the non-confocal etalon of the FPQFA but differs from the confocal etalon 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 FPQSA, the etalon 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.

† Infrasil is a registered trademark of Heraeus Quarzglas.

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

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

$$FSR = c/2dn(\lambda)\,,$$

where *c* is the speed of light, *d* is the etalon length, and *n(λ)* is the refractive index of the mirror substrate. N.B. the factor of 2 in the denominator as for a plano-plano etalon instead of a factor 4 as in a confocal etalon such as the Thorlabs' SA series of scanning Fabry-Pérot interferometers.

1.4 Technical Data

1.4.1 Specifications

Item #		FPQSA-5	FPQSA-8	FPQSA-13
Wavelength Range		550 – 845 nm	845 – 1300 nm	1270 – 2000 nm
Mirror Substrate		Infrasil® 302		
Free Spectral Range		30 GHz		
Finesse		>300		
Resolution		<100 MHz		
On-Resonance Transmission		>80 %		
Extinction (Excluding Higher Order Modes)		30 dB (Typ.)		
Etalon Length		3.4 mm		
Recommended Temperature Controller		Item # TC300B		
Temperature Scanning Range		25 to 70 ºC		
Temperature Scanning Range 1 FSR (550 ≤ λ ≤ 2000 nm)		~10·(λ/845) + 3 ºC		
Heater Resistance		50 Ω ± 10 %		
Thermistor Model (10 kΩ)		TDK B57230V2103F260		
Thermistor Electrical Specifications	**R_0 (T_0 = 25 °C)**	10 kΩ ± 1 %		
	$B_{25/100}$	3455 K ± 1 %		

1.4.2 Mechanical Drawings

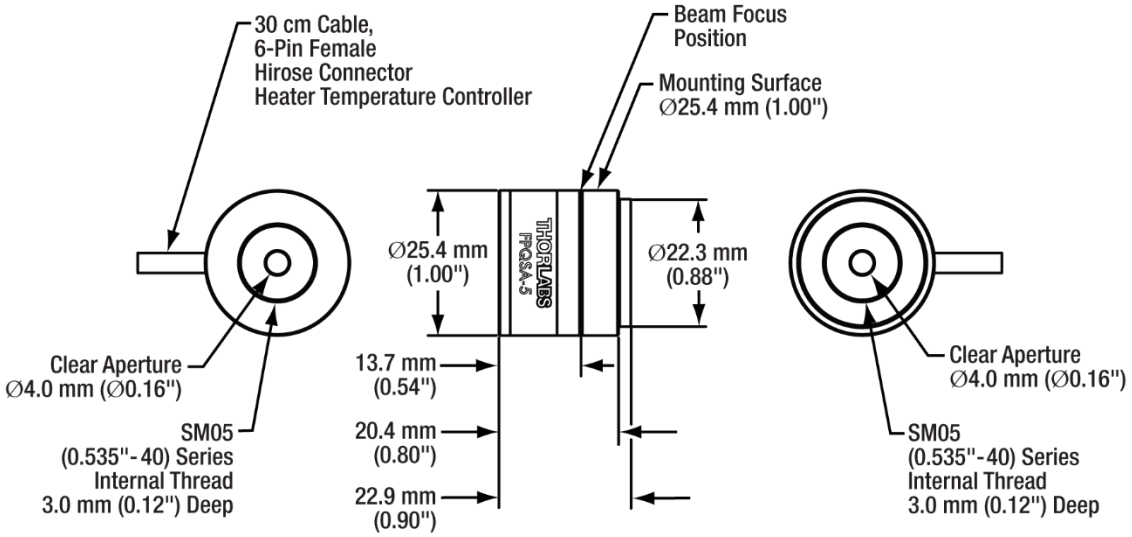


Figure 2 Mechanical Drawing for FPQSA-5, FPQSA-8, and FPQSA-13

1.5 Pin Diagram

The FPQSA cable is terminated with a 6-pin Hirose female connector to which the supplied 1 m male-male Hirose cable is connected. The other end of the cable is connected to one of the channels on the TC300B. The pin diagram of the FPQSA female connector is:

Pin	Description
1	Heater Positive
2	Heater Negative
3	N/C
4	NTC 10 kΩ Thermistor
5	NTC 10 kΩ Thermistor
6	N/C



Figure 3 FPQSA Pin Diagram

Chapter 2 Safety

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

NOTICE Never apply temperatures above 70 ^{o} C as it may damage the FPQSA.

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

- FPQSA Temperature-Controlled Narrow Bandpass Fabry-Pérot Filter
- 2 SM05CP2 End Caps
- 1 male-male Hirose Cable, 1 m

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 supplied cable to the FPQSA and the TC300B thermal controller 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 FPQSA.

4.1 General

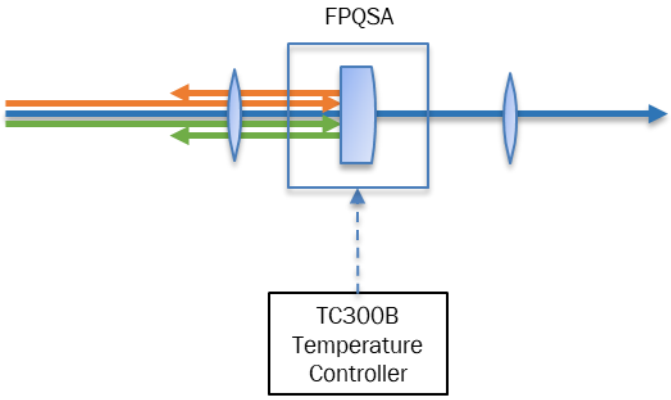


Figure 4 The FPQSA used in a typical application, rejecting the off-resonance wavelengths.

The FPQSA Temperature-Controlled Narrow Bandpass Fabry-Pérot Filter can be used to suppress wavelengths that are off the etalon resonant transmission, see Figure 4. Here, the FPQSA is connected to a temperature controller, TC300B, set to High Resolution mode. The FPQSA transmits a part of the incoming light's spectrum

given by the filter's Lorentzian-shaped transmittance. The transmitted light is collected by the down-stream optics for further use.

Whenever the FPQSA is used, it is very important to properly shape the illuminating light beam to match the fundamental mode supported by the etalon. This is also known as mode matching and will be discussed in the following sections.

4.2 Confined etalon mode

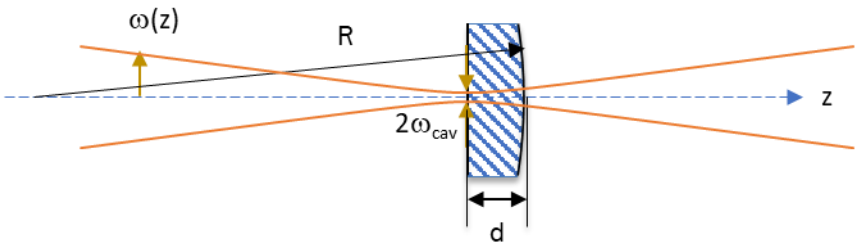


Figure 5 A plano-concave etalon illuminated with a mode matching the etalon fundamental mode.

The plano-concave etalon 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 etalon length d and the radius of curvature of the curved mirror R by:

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

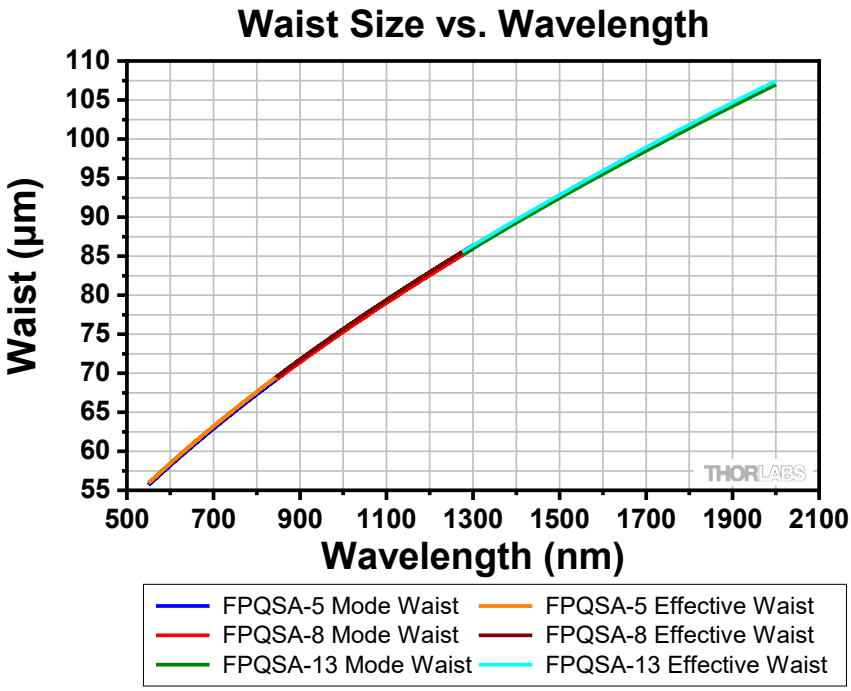


Figure 6 ***Fundamental etalon mode and effective waist size for the FPQSA versus wavelength.***

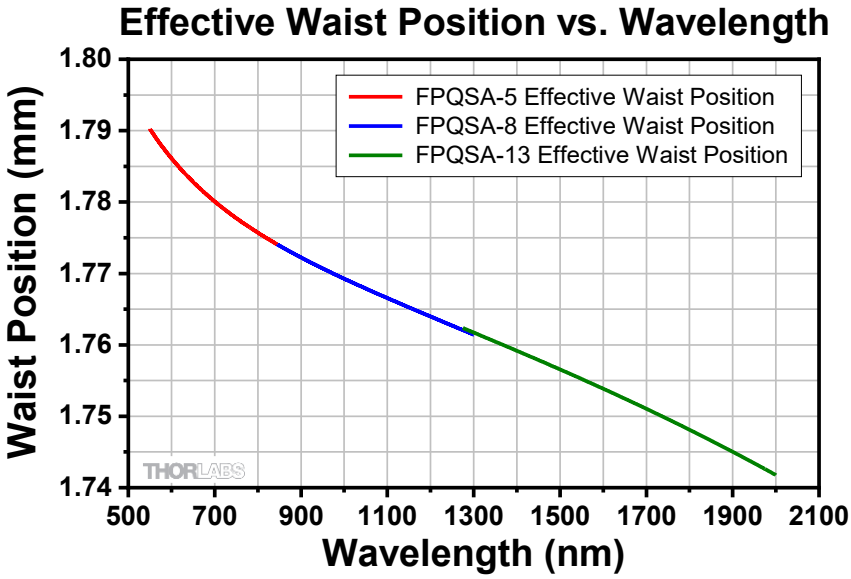


Figure 7 ***Effective waist position for the FPQSA versus wavelength.***

For the FPQSA etalon, d = 3.4 mm, and R = 200 mm. The value of ω_{cav} depends on the wavelength, with representative values plotted in Figure 6.

If the light transmitted by the etalon should be collected by downstream optics, it is important to consider the impact of the etalon. The propagation in the substrate and spherical mirror will slightly affect the waist size and waist position as seen after the spherical mirror in Figure 5. This effective waist size is also plotted in Figure 6, and

the position relative to the actual waist position (coinciding with the flat mirror) is plotted in Figure 7. A positive effective waist position means that the effective waist is located after the real waist position in Figure 5.

It is important to recognize that the geometry of this confined etalon mode is completely determined by the etalon geometry, the wavelength, and the refractive index of the substrate, independently of the light incident upon the etalon. In practice, we wish to "mode-match" the incoming light to the etalon 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 etalon mode, and orienting the ingoing light in the same direction as the etalon 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 in turn.

4.3.1 Free-space beam

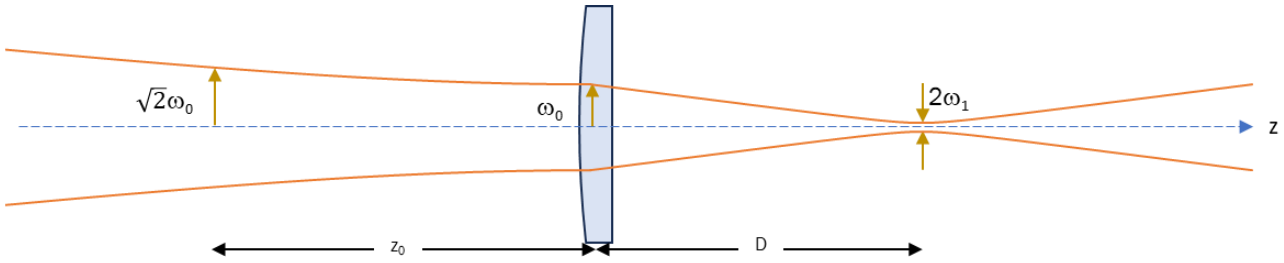


Figure 8 A Gaussian beam is focused by a lens with focal length f a distance D from the lens.

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

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

a distance

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

from the lens, as shown in Figure 8. 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 an etalon 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} = 60 µm at λ = 633 nm, gives a focal length of f = 167 mm. To mode-match an incident beam of the same radius ω_0 to an etalon mode radius ω_{cav} = 86 µm at λ = 1300 nm, a focal length of f = 116 mm is needed. Lenses with focal lengths of f = 175 mm in the first case, and f = 125 mm (or a combination of two lenses with f=125 mm and f = 1000 mm resulting in a focal length f = 111 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

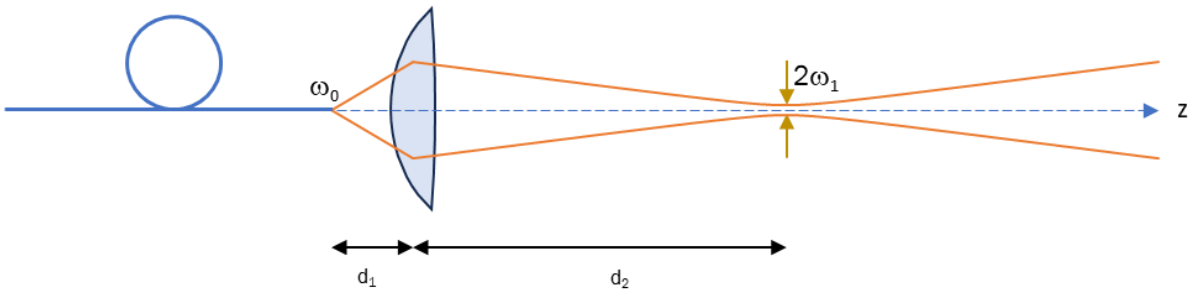


Figure 9 Mode-matching from an optical fiber.

The other situation that occurs frequently is that the light to be injected into the etalon 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 = 2.07 µm. Note that this slightly smaller than half of the given 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 taken to be

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

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 9. In practice, one chooses a collimator with a focal length that will give a convenient distance d_2 to the etalon. For example, with ω_0 = 2.07 µm and $\omega_1 = \omega_{cav}$ = 69 µm, one finds

$$d_1 = 1.03f$$
$$d_2 = 34.4f\ .$$

A collimator with a focal length of f = 4.6 mm, such as Thorlabs CFC5A, would give d_1 = 4.74 mm and d_2 = 158 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 of which two are presented here.

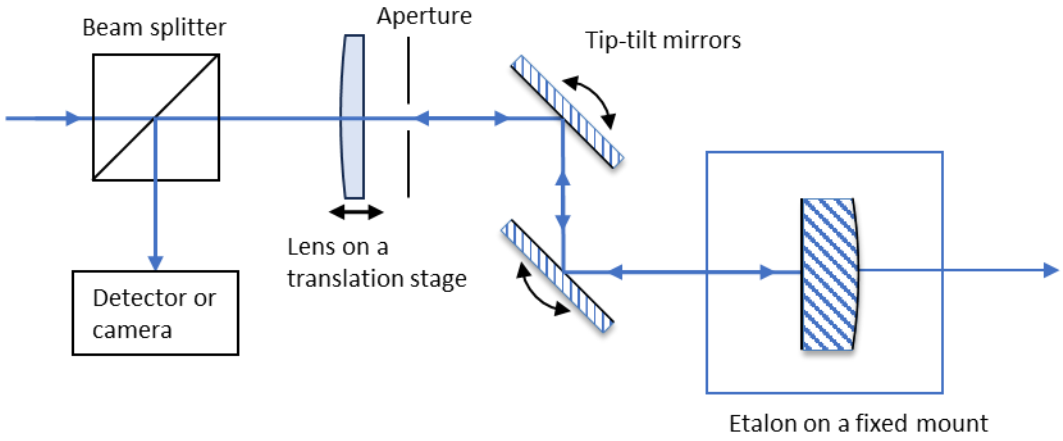


Figure 10 Example of an alignment setup with the five necessary degrees of freedom for mode-matching (only three degrees of freedom is shown in the figure), where the FPQSA is used as a tunable optical filter.

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

Figure 10 illustrates a setup where the etalon is fixed, and the incident beam is shaped to match the etalon mode and aligned to the etalon. This setup is suitable when the light transmitted through the etalon is collected by downstream optics for further processing since the direction of that light is set by the etalon 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

$$z_{cav} = \sqrt{d(R-d)} = 25.8mm$$

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 etalon, 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 etalon mirror. Aligning the mirrors such that light reflected by the etalon passes back through the aperture ensures that the injected beam is perpendicular to the etalon input coupling mirror. In a fiber system, the same goals may be achieved by using a circulator and optimizing the reflected power.

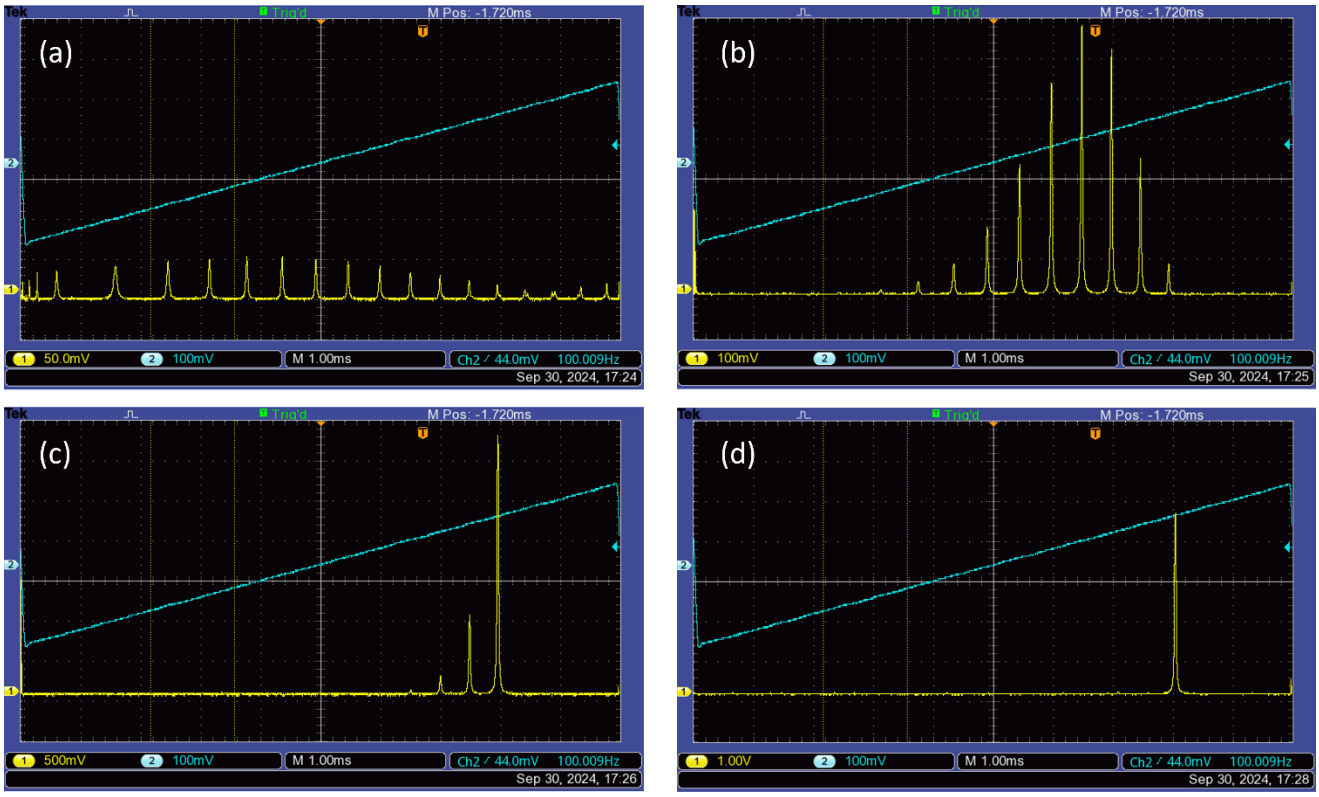


Figure 11 Oscilloscope signal (a) after initial rough alignment, (b) after first iteration, (c) after second iteration, (d) when mode-matching is achieved. Note the different voltage scale in the figures.

After this first rough alignment, when placing a detector after the etalon and displaying the signal on an oscilloscope, one can expect to see a transmission signal as the laser wavelength is modulated with sawtooth wave, see Figure 11a. To optimize the alignment of the two steering mirrors, the suggested procedure is as follows:

- With the mirror furthest from the etalon, 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 11d). If the mode-matching is still not satisfactory, it may be necessary to translate the lens axially or change the focal length.

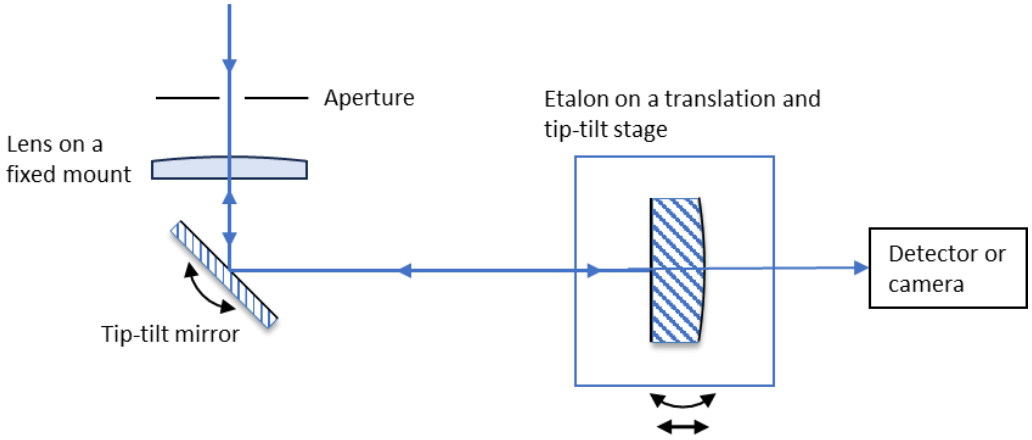


Figure 12 Example of an alignment setup with the five necessary degrees of freedom for mode-matching (only three degrees of freedom is shown in the figure), where the FPQSA is used as a frequency scanning filter.

There are many alternatives to the setup illustrated in Figure 10 in which the etalon is fixed, and two steering mirrors are used for alignment. One solution compatible with Thorlabs' XT66 66 mm optical rails is to mount the FPQSA in a CP35(/M) cage plate held by four ER3 cage rods and fastened on the rail with two RCA1 cage plates.

Another scheme has the etalon itself on a kinematic mirror mount (we recommend the Polaris-K1E mount), providing two degrees of freedom, in which case only one steering mirror is needed to provide two more degrees of freedom, see Figure 12.

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

4.4 FPQSA Mounting

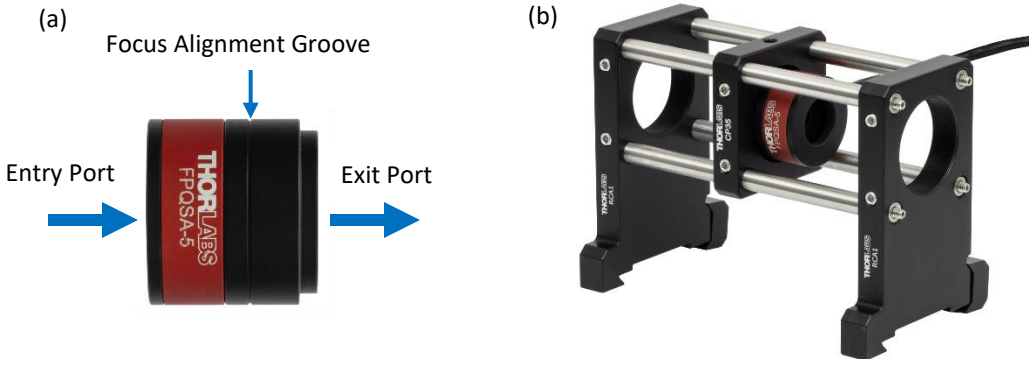


Figure 13 (a) Entry and exit port, and focus alignment groove on housing indicating the focus position. (b) FPQSA mounted in a CP35(/M) cage plate held by cage rods and RCA1 cage plates.

When mounting the FPQSA 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 13a. 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 etalon mirror. To facilitate alignment for the user, when the FPQSA is mounted in a Thorlabs mirror holder for Ø1"-optics (such as the CP35(/M) or Polaris-K1E), the focus alignment groove coincides with the mirror holder front face, see Figure 13b.

If needed, the FPQSA 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 Temperature Controller

NOTICE Never apply temperatures above 70 °C as it may damage the FPQSA.

Although the FPQSA is designed to be used seamlessly in combination with the TC300B Heater and TEC Temperature Controller, it can be used with any heater controller if all specifications in Section 4.5.1 are met. However, Thorlabs does not guarantee any performance or provide support if the user uses any other temperature controller than the Thorlabs TC300B.

4.5.1 Temperature Controller Settings

When using the FPQSA with the TC300B temperature controller, only one FPQSA should be connected for optimal performance and the TC300B should be in High Resolution mode. Settings not to be exceeded are:

- Mode Set: Heater
- Sensor: NTC1
- Beta: 3455
- R0 Value: 10 kΩ
- T0 Value: 25 °C
- Temp Min: 25 °C
- Temp Max: 70 °C
- Temp Res: HIGH RES
- Voltage Max: 12.0 V
- Current Max: 0.8 A

When using the FPQSA-TC300B combination, it is important to keep both the filter and the controller in a temperature-controlled environment where the temperature variation does not exceed ± 0.2 °C, see Thermal Stability plot on the product page **https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=16346**. If the temperature variation is larger than ± 0.2 °C, the performance of the FPQSA cannot be guaranteed.

For the TC300B to keep the FPQSA etalon at a constant temperature, the PID parameters in the temperature control loop must be set. The optimal settings depend on several factors: the operating temperature, the environmental temperature, and variations from device to device. Therefore, the PID parameters should be set with the filter and temperature controller in their respective environment and at the temperature at which they will be used in the application. The TC300B manual provides a description for both manual and automatic tuning of the PID parameters.

The recommended procedure for setting the PID parameters when using the FPQSA is:

1. Place both the FPQSA and the TC300B in their temperature-controlled environment.
2. Connect the FPQSA to the TC300B with the supplied 1 m male-male Hirose cable.
3. Set the FPQSA temperature to a typical temperature at which it will be used. This temperature should be at least 5 ^{o}C above the environmental temperature.
4. Set the PID Period to the smallest value, 0.020 s.
5. Perform a PID Auto-Tune and accept the new settings.
6. Start the TC300B GUI and plot the set and actual temperature.
7. Change the temperature ± 0.010 ^{o}C and fine tune the I Share parameter to minimize the size and the number of overshoots. If a satisfactory result cannot be achieved, the P and D parameters can also be tuned.

4.5.2 Temperature scan control

When the incoming light has been mode-matched to the FPQSA according to Section 4.3, the TC300B can be used to tune the FPQSA resonant transmission to the desired frequency with high accuracy and stability. But first it is necessary to measure the exact FPQSA temperature response, i.e. how much the frequency changes per degree (MHz/^{o}C).

1. Place the FPQSA and the TC300B in their temperature-controlled environments where the temperature variation is less than ± 0.2 ^{o}C
2. Increase the temperature to scan over 1 FSR (FPQSA Specifications Table in Section 1.4.1) in small temperature steps (~0.005 ^{o}C). Let the temperature stabilize for ~2 minutes at each temperature step before measuring the transmitted signal through the filter.
3. Measure the temperature difference between two resonant transmission peaks from the incoming light (DT), and calculate the temperature response as f_T = 30 GHz/DT.

4.5.3 Optimizing FPQSA transmission

When tuning the FPQSA to a frequency offset from the incoming laser light, such as when filtering out a weak signal in the presence of strong pump beam, it is recommended to optimize the resonant transmission frequency in addition to parking the filter at a temperature given by filter's temperature response, f_T. One suggested method is to use the Golden Section Search algorithm where the temperature is allowed to stabilize for 2 minutes at every step. This algorithm is designed to find an extremum (minimum or maximum) of a function inside an interval at as few steps as possible.

Chapter 5 Maintenance and Cleaning

There are no user serviceable parts on the FPQSA, 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 FPQSA housing can be cleaned with a damp lint free cloth. Make sure not to let any water enter the entry and exit ports.

The mirrors which are visible through the entry and exit ports can only be cleaned with clean compressed air. Never touch the mirrors with a physical object.

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 FPQSA is properly connected to the temperature controller.
	Verify that there are no warning or error signals from the temperature controller.
	Verify that the temperature is on and is generating the right output.
	Set the controller to a higher temperature (~50 ºC) and verify that the FPQSA gets warmer by touching it by the side. Do not touch the entrance and exit ports.
	Verify that the transmitted or reflected beam is not obstructed and hits the detector properly.
	Scan the laser wavelength while the FPQSA temperature is constant (or temperature controller is off). Verify that the transmitted signal is as in Figure 11.
	Increase the temperature scan range to make sure the frequency scan is at least 1 FSR, see FPQSA Specifications Table in Section 1.4.1.

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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