FPI 100

Fabry-Perot Interferometer

Manual

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Serial Number:____________________

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1 Introduction

The FPI 100 is a piezoelectrically scanned confocal Fabry-Perot Interferometer that combines high finesse (F) and ease of alignment with the flexibility of using it as a stable reference cavity for applications from the UV toIR range of the optical spectrum. Two different mirror radii are available, 75 mm and 18.75 mm, which give a free spectral range (FSR) of 1GHz and 4GHZ, respectively.

1.1 Theory of Operation

When illuminated by monochromatic light rays close to the axis, a multiple beam interference pattern is produced near the center of the interferometer. At precisely the confocal spacing, each mirror images the other back upon itself so that a paraxial ray is re-entrant, i.e. falls back upon itself after four traversals of the interferometer. This is not strictly true for real rays, where successive traversals of the interferometer are not perfectly re-entrant but for paths close to the axis multiple reflections will continue to intersect at the beam waist, creating an interference fringe pattern. Four traversals of the cavity mean that the transmitted spectrum is reproduced with every quarter wavelength (λ /4) change in the mirror separation. Consequently the free spectral range is given by

$$FSR = c/4nd$$

where *c* is the velocity of light, *n* is the refractive index of the air between the mirrors, and *d* is the distance between the mirrors.

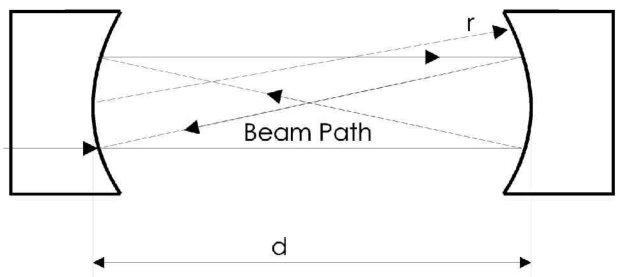


Figure 1 Confocal Interferometer Configuration

The etalon makes use of spherical mirrors whose radius of curvature *r* is equal to the spacing *d* between the mirrors. Therefore, the FSR of a confocal etalon is fixed by the choice of mirrors. This is a disadvantage when compared to a plane parallel Fabry-Perot Interferometer, which can be used at any mirror spacing. On the other hand the spherical mirror interferometer is much less sensitive to mirror alignment because it is not necessary to maintain mirror parallelism. In addition, the focusing effect of curved mirrors results in a mode with a small diameter on the mirror surface, minimizing the possible finesse degradation due to the mirror surface imperfections. Only the mirror separation and alignment with incident light beam are critical for the performance of a spectrum analyzer, which makes the confocal spectrum analyzer extremely simple to use.

1.2 Resolution and Finesse

The spectral resolution of any Fabry-Perot interferometer is *FSR/F*. For a given FSR, the resolution becomes higher for higher reflectivity mirrors. At high reflectivity the surface quality of the mirrors may also limit the resolution. (See paragraph 6.4). Therefore, there are practical limits in the quest of arbitrarily high resolution. One is that the surface quality is bounded by the limitations of mirror polishing. Another is that higher reflectivity produces lower etalon transmission, as coating absorption and substrate scattering losses become magnified by a factor of $(1\text{-}R)^{-1}$. Finesse as high as 10^5 has been reported for super-polished substrates with low-loss coatings. However, such mirrors are environmentally sensitive, and are usually mounted in hermetically sealed housings.

By contrast, the FPI 100 uses mirrors with moderately high reflectivity (> 99,7%), which can be produced in almost any spectral region between 350 and 1700 nm with losses low enough for high interferometer transmission.

By request the FPI 100 can also be supplied with interchangeable mirrors. Changing to another spectral region usually requires only an internal mirror change and the adaption of the mirror spacings rather than a complete etalon change.

The FPI 100 is intended as a spectral analysis system as well as a stable reference cavity. Its resolution depends on the quality of the mirror coating and surface and is separately specified for each interferometer. A typical resolution is 5 MHz by using a mirror set having a free spectral range of 1GHz and a finesse of 200. In applications requiring a high long-term absolute stability the FPI 100 can also be temperature stabilized.

Typical applications of the spectrum analyzer include mode structure characterization, the measurement of laser linewidths, laser frequency stability and the frequency stabilization of lasers.

Optical spectrum analyzers are commonly used with almost every type of laser. Please contact TOPTICA Photonics AG for further information about Fabry-Perot applications and operating principles.

2 Inspection after Delivery

The FPI 100 is packed in a carton designed to give maximum protection during shipment. If the outside of the shipping carton is damaged, notify your shipping department immediately. The shipping department may wish to notify the carrier at this point.

If the shipping carton is undamaged externally, the instrument should be removed from the carton. If any damage is evident visually or if any rattling can be heard if the unit is shaken lightly, notify TOPTICA Photonics AG and your shipping department. It is advisable to save the carton for future storage or transportation.

The complete system consists of the Parts shown in Figure 2.

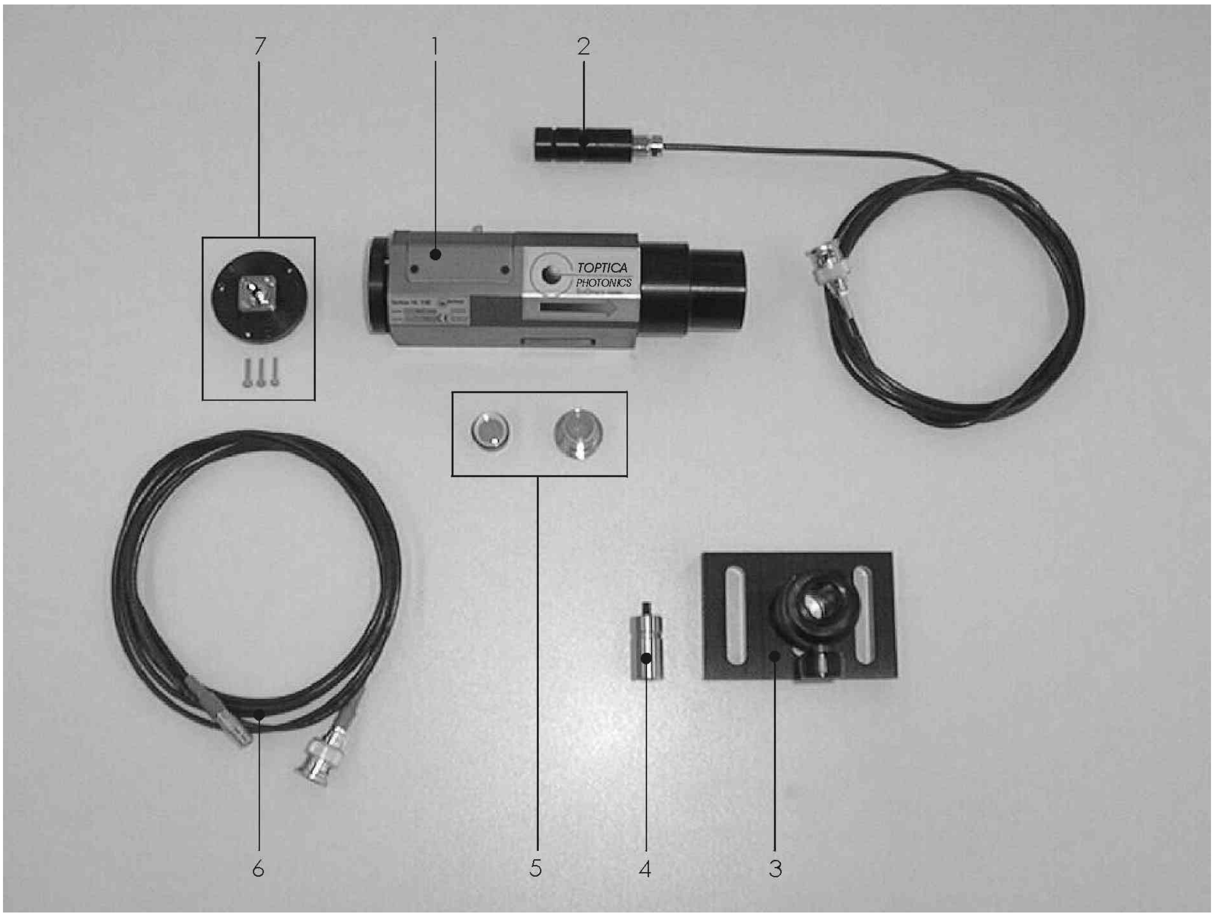


Figure 2 The FPI 100 System

(1) FPI Assembly (etalon body with mounted mirror on a PZT, resonator adjustment body with mounted mirror, cover plate
(2) Photodetector housing with mounted photodiode and cable connecting the photodetector with an oscilloscope or a detector amplifier
(3) Baseplate
(4) Post
(5) Additional set of mirrors (optional)
(6) SMB cable for driving the piezoelectric actuator and connecting the Scan Control SC 100 to the FPI 100
(7) Fiber Coupling Adaptor (optional)

The FPI contains the mirror set specified on the order.
The instrument you have received has been fully tested at the factory prior to shipment and meets all specifications. As with any optical instrument it is important that it is maintained in a clean state.

In some cases optional accessories are supplied with the FPI 100.

Scan Control SC 100

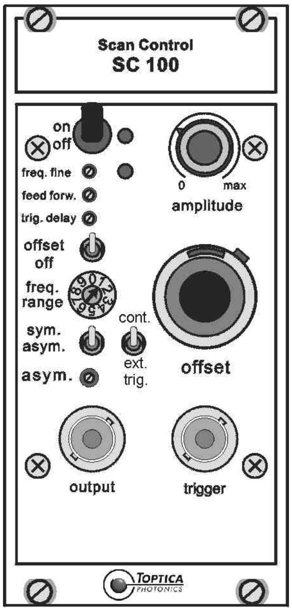


Figure 3 Scan Control SC 100 (optional)

PDA 100

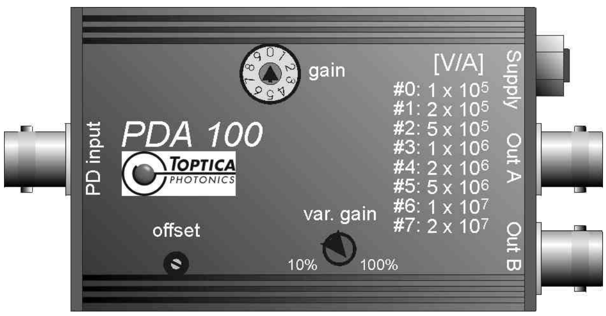


Figure 4 Photo Diode Amplifier PDA 100 (optional)

3 Description of Components of the FPI 100 System

The FPI 100 System consists of the parts shown in Figure 2. An inside view of the etalon body is given in Figure 5.

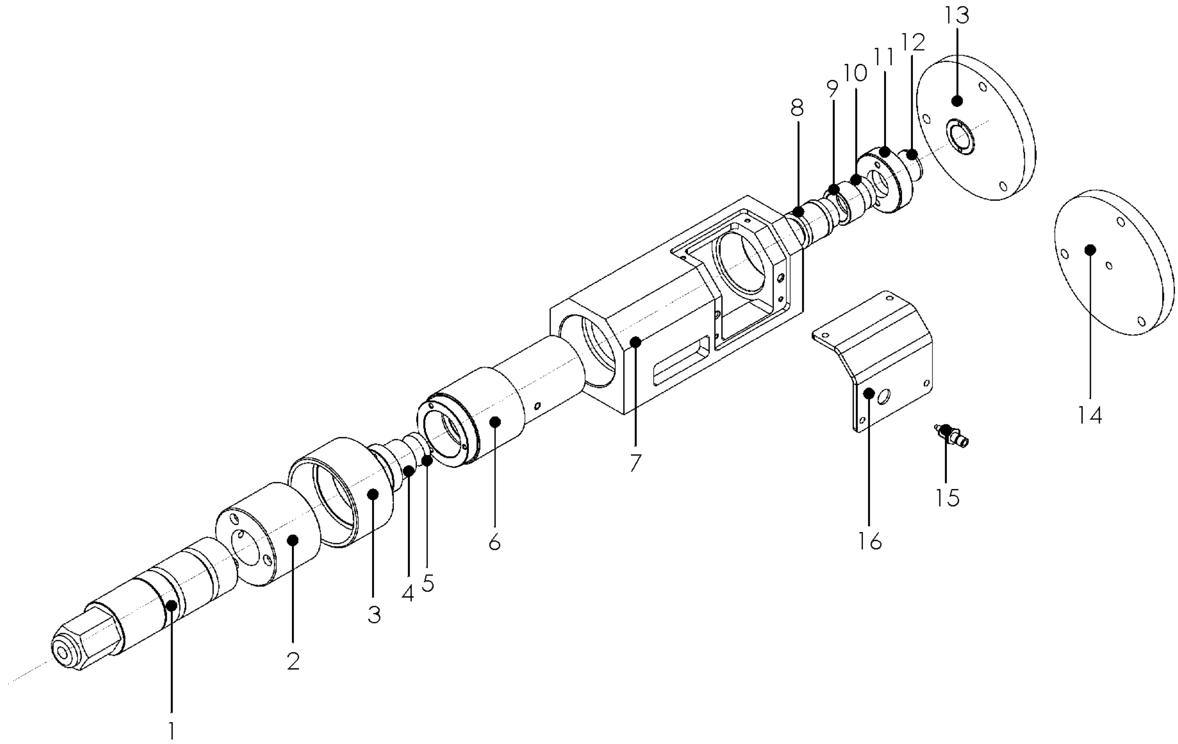


Figure 5 Inside view of the FPI 100

(1) Photo detector assembly
(2) Adjusting Knob
(3) Locking Ring
(4) Rear Mirror Holder
(5) Rear Mirror
(6) Resonator Adjustment Body
(7) Etalon Body
(8) Piezo
(9) Front Mirror Holder
(10) Front Mirror
(11) Lens Holder
(12) Matching Lens
(13) Fiber Coupling Assembly
(14) Aperture Plate
(15) SMB-connector
(16) Cover

3.1 Mechanics and Optics

The FPI 100 consists of the coupling optics mounted into a lens barrel, a concave mirror set mounted on a piezo actuator (front mirror) and into the adjusting knob (rear mirror) allowing a smooth, precise positioning of the cavity spacing and an etalon body picking up the piezo, the lens barrel and the adjusting knob.

The etalon assembly consists of the following parts (refer to Figure 5):

(7)	**Etalon body:**	The etalon body is made of aluminium for better thermal conductivity. A temperature stabilization by mounting the etalon body onto a peltier element is advisable if a long term stability of the FPI 100 is desired.
(12)	**Matching Lens:**	An input lens with an aperture of 10mm and a focal length of 50mm for a FSR of 1GHz (30mm for a FSR of 4 GHz) is mounted inside the lens barrel. It is positioned so that a collimated input beam will be focused on the center of the etalon and provide the minimum mode diameter inside the cavity. This minimizes finesse degradation due to the effect of mirror aberrations and figure errors. The input lens can be supplied ar-coated for the respective spectral range on request.
(5,10)	**Mirrors:**	The mirrors are spaced at a distance equal to their radius of curvature, either 75 mm (FSR 1GHz) or 18,75 mm (FSR 4 GHz). The front mirror is mounted on a cylindrical piezoelectric element which contracts with applied voltage. The rear mirror is mounted into the resonator adjustment body.
(2)	**Adjusting Knob**:	The mirror spacing is set by rotating the adjusting knob on the end of the etalon assembly. The adjusting knob moves the resonator adjustment body and with it the rear mirror holder relative to the fixed front mirror. A thread pitch of 3turns per mm allows smooth, precise adjustment of the mirror separation.
(3)	**Locking Ring:**	The locking ring allows the user to lock the adjusting knob and with it the resonator adjustment body in place once the mirror spacing is set.

3.2 SC 100 Scan Control (Optional)

The SC 100 Scan Control provides a voltage ramp for scanning the spectrum analyzer through its free spectral range. Front panel controls allow the user to adjust the ramp characteristics. BNC connectors on the front panel provide signal monitoring and external trigger output.

Refer to the SC 100 manual from TOPTICA Photonics AG for further informations about the SC 100 Scan Control.

3.3 Photodetector

The Photodetector detects the laser light transmitted through the etalon cavity for displaying it on an oscilloscope.

NOTE !	The photodetector is neither amplified nor terminated. It is therefore advisable to either terminate the photodetector with 50-1000 Ohm or to use a fast commercially available detector amplifier, depending on the laser output power.

The detector amplifier PDA 100 designed for the FPI 100 is available from TOPTICA Photonics AG.

4 Operation

4.1 Electronic Setup

Connect the output ramp of the ramp generator to the FPI 100 using the SMB-connector on the etalon body.

NOTE !	The voltage output ramp should not exceed 0-500 V!

Connect a BNC cable from the output ramp of the ramp generator to an oscilloscope input.
Connect a BNC cable from the trigger output of the ramp generator to the oscilloscope trigger.
Connect the photodetector to an oscilloscope input using the BNC cable provided with the FPI 100.

Start operating the SC 100 (or similar ramp generator). Set the ramp duration to a low value of about 20 milliseconds. Adjust the amplitude and voltage offset so that a ramp of at least 30 V pp is displayed on the oscilloscope without being clipped. These settings produce at least one interferometer free spectral range displayed on the oscilloscope.

4.2 Optical Alignment

The FPI 100 is designed for excellent resolution and stability. The most important factor in fully realizing these features is careful alignment of the etalon. The following instructions assume a stable, single frequency laser. Although it is not a requirement for proper alignment, a stable, single frequency is the most convenient source for alignment, particularly for the first time user, because it produces only one peak per free spectral range.

Once the preliminary electronic settings of the preceding section are complete, the next step is to align the laser to the etalon. Note that the detector can remain attached to the spectrum analyzer during these adjustments because it is flexible with respect to the cable supplied with the FPI 100.

4.2.1 Coarse Cavity Adjustment

First make sure that the interferometer assembly is complete (see Figure 5). Although the etalon is shipped factory-aligned, it may be necessary to slightly adjust the mirror spacing. This is also necessary after changing mirror sets.

Align the laser beam so that it is traveling parallel to the optical table or surface on which the FPI 100 is mounted. Use a mirror or a mirror pair in order to center the laser beam on the aperture of the FPI 100. Now adjust the laser beam by using the above mirror pair so that the light reflected from the etalon mirrors is directed back onto the incident beam. Directing the incident beam through a small aperture in a white viewing card placed about 30 cm in front of the etalon will aid in viewing and aligning the reflected beam. Using an infrared laser implies either using a infrared camera or a infrared sensor card in order to monitor the alignment.

It should now be possible to see a signal on the oscilloscope. By comparing this signal with the signals in Figure 7 through Figure 13 a coarse estimation about the necessary alignment should be possible.

If no signal seen, refer to Paragraph 5, Troubleshooting.

4.2.2 Optimizing the Cavity Alignment

Figure 6 Fine adjustment of mirror spacing

The first step towards attaining the high performance of which the FPI 100 is capable is to set the cavity spacing *d* equal to the mirror radii *r*. This is the confocal condition. Therefore a fine adjustment of the mirror spacing by slightly turning the adjusting knob (2) has to be accomplished. Before turning the adjusting knob, loosen the locking ring (3).

NOTE !	If you are using the Fiber Coupling with your FPI 100, refer to Paragraph 4.3 for special instructions before beginning the optical alignment of the system.

Rotate Adjusting Knob (2) slowly, periodically stopping to observe the signal on the oscilloscope, until all the peaks in each free spectral range become degenerate and collapse into one peak. As this happens the amplitude will increase dramatically.

Continue to adjust the cavity spacing until the peak shape is as symmetrical as possible. Refer to Figure 7 to Figure 13. Then again adjust the position of the laser beam by using the above mirror pair to maximize the peak height. In general, the peak height will be more sensitive to tilt than it will be to translation.

NOTE !	It may become necessary to prevent the back reflection from destabilizing the laser. Inserting an optical isolator or a neutral density filter in the input beam path will reduce the amount of light reflected back into the laser. Otherwise the laser beam has to be slightly tilted from the interferometer axes taking finesse degradation and unsymmetrical resonance peaks into account.

Continue to adjust the cavity spacing to produce peaks that are tallest and most symmetrical in shape. Once this is done the Locking Ring (3) can be fastened to lock the cavity in place and reduce mechanical vibration-induced noise. When the peak position has stabilized, the amplitude and duration control on the ramp generator can be used to expand the display so that an individual peak is easily resolved. Any final tilt and translation alignment can be done with greater accuracy while examining a single peak.

As one continues to improve the signal from the spectrum analyzer, one frequently achieves the condition of partial mode matching. Partial mode matching will cause the peaks in adjacent free spectral ranges to be of unequal intensity. There is no problem with operating in this condition so long as one is aware that the weaker signal is simply the next interferometer order, and not a second frequency in the laser output. When the interferometer is completely mode matched, the FSR doubles and the peak height also doubles. See Appendix A for more information and mode matching.

Figure 13 shows a portion of one FSR obtained with a properly aligned FPI 100 System. The source was a grating stabilized single mode diode laser working at 780 nm.

4.2.3 Interferometer Spectres

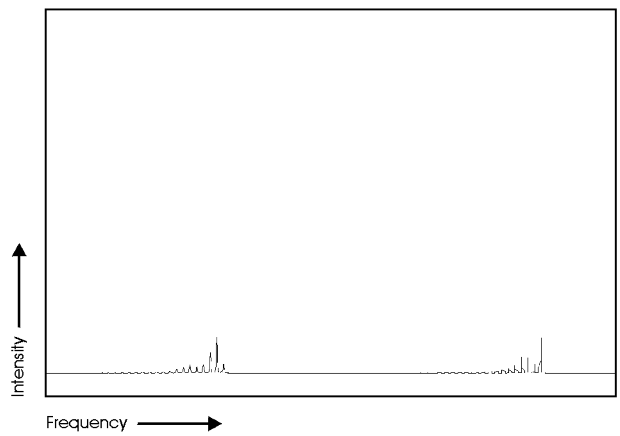


Figure 7 Cavity Spacing is too large by 1 mm.

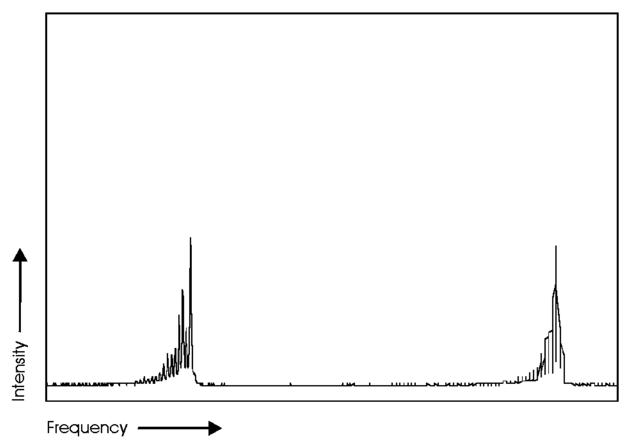


Figure 8 Cavity Spacing is too large by 0.6 mm corresponding to two turns of the Adjusting Knob.

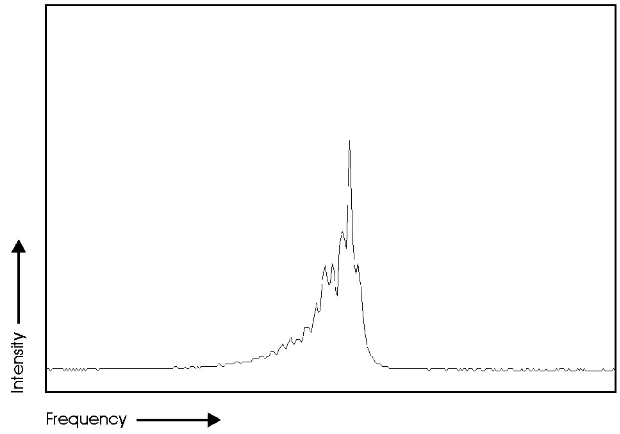


Figure 9 Cavity Spacing is too large by 0.3 mm corresponding to one turn of the Adjusting Knob.

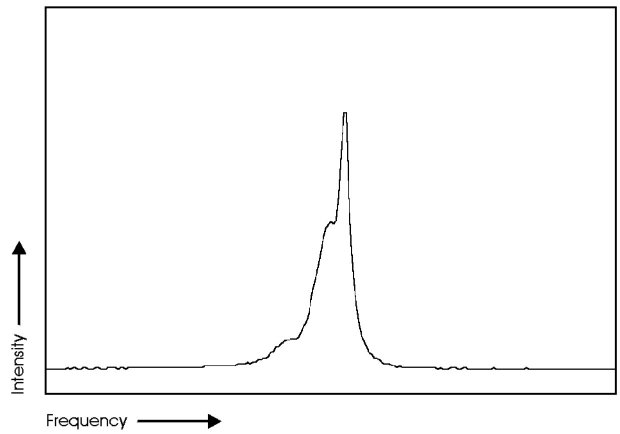


Figure 10 Cavity Spacing is too large by 0.15 mm corresponding to a half turn of the Adjusting Knob.

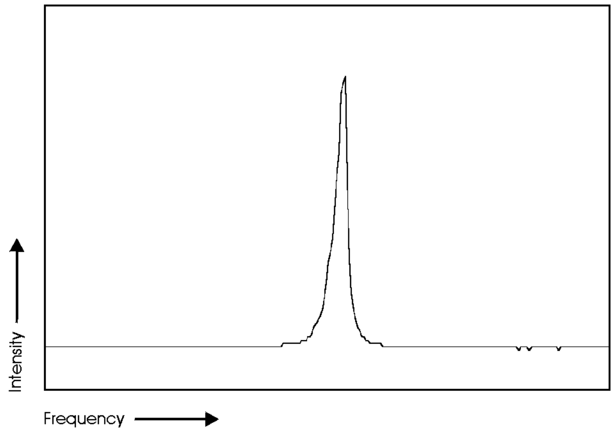


Figure 11 Cavity Spacing is too large by 0.075 mm corresponding to a quarter turn of the Adjusting Knob.

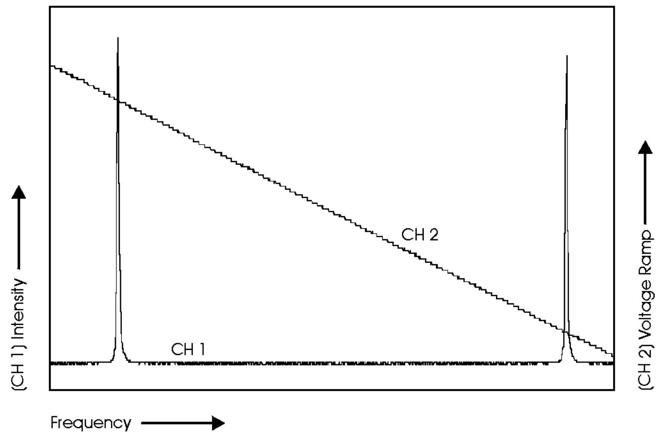


Figure 12 Cavity Spacing is almost perfect (*d* = *r*). The Locking Screws should now be fastened. The two modes are separated by 1 GHz corresponding to the free spectral range of the FPI 100.

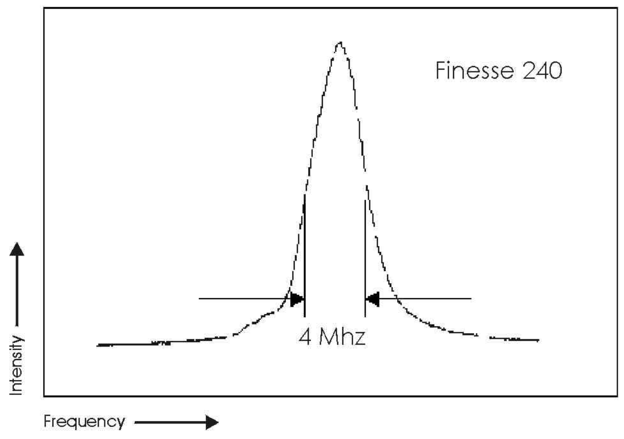


Figure 13 The Finesse is computed by comparison with Figure 12 and taking the free spectral range into account. The laser used for the measurement had a wavelenght of 780 nm. The photodetector was terminated by 50 Ohms and the signal amplified by 10^4.

4.3 Fiber Coupling Mounting and Alignment

NOTE !	Before using the fiber option make sure that the mirror spacing is optimized (see paragraph 4.2.2). In order to achieve the best performance of the FPI 100 it is advisable to use a single mode fiber to couple the laser into the interferometer. However, a quiet good performance is also possible by using a multi-mode fiber.

For exchanging the aperture plate to the fiber coupling assembly and collimation of the laser beam follow the steps given below.

1. Unscrew screws 1-3 (see Figure 14) and remove aperture plate.

DANGER !	Do not look into the laser beam under conditions with exceed the limits specified by the United States Food and Drug Administration, Department of Health and Human Services, Center for Devices and Radiological Health, 21 CFR 1040.10 and 2 CFR 1040.11. Take precautions to eliminate exposure to a direct or reflected beam. When carrying out adjustments always wear laser safety goggles.

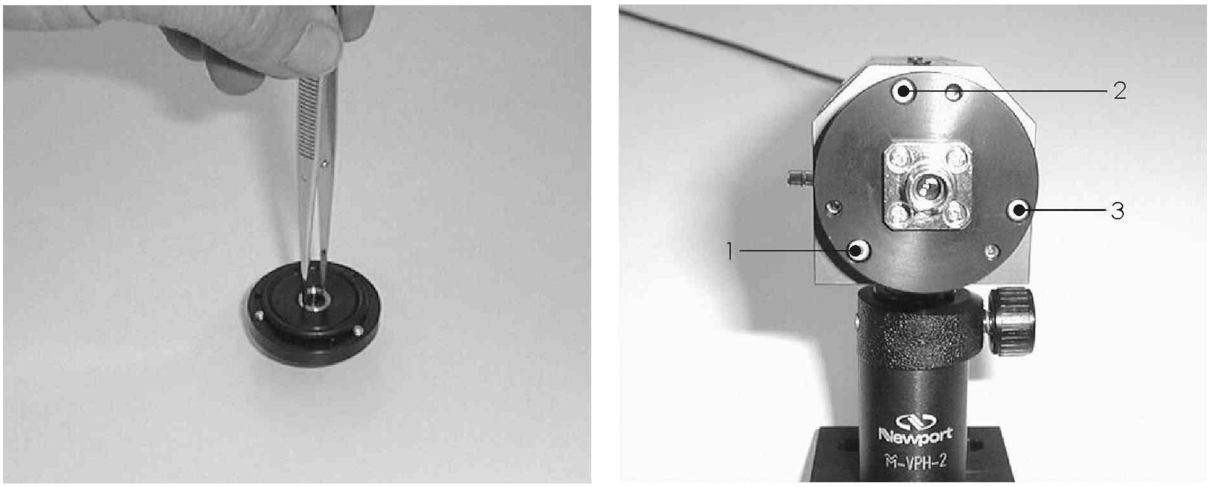


Figure 14 Aligning and mounting fiber coupling assembly

2. For optimum coupling to the interferometer, the input beam propagating through the fiber coupling assembly should be collimated by adjusting the position of the collimating lens. To check whether the laser beam is properly collimated, connect fiber cable to fiber coupling assembly, switch on laser and observe laser beam in distances from 1 to 6 m. For collimating beam adjust collimating lens by the aid of tweezers.

3. Mount fiber coupling assembly to the etalon body by fixing screws 1-3.

It should now be possible to see a signal on the oscilloscope. The alignment can then be optimized by tilting the fiber coupling assembly using the six screws at its front.

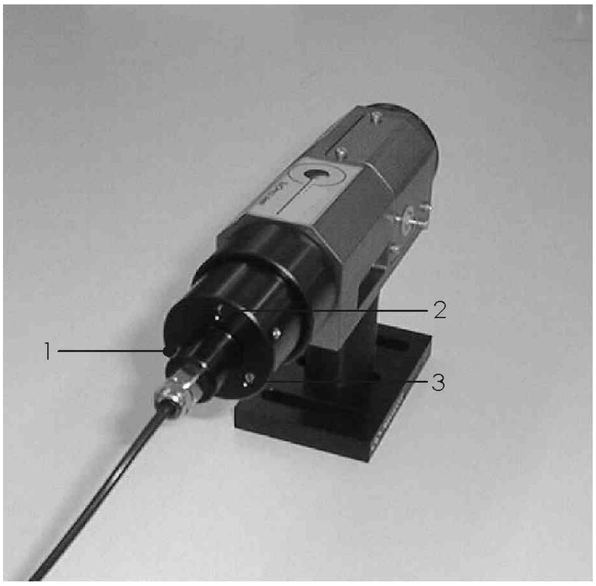
If no signal detected, the collimation of the laser beam after the fiber coupling assembly should be investigated and readjusted if necessary.

4.4 Changing Mirror Sets

The FPI 100 offers the flexibility of interchangeable mirror sets for operation at different wavelengths or the alternate FSR. A change of the operating wavelength involves changing the mirrors and it is important also to verify that the proper photodetector is being used.
For changing the mirror set, please follow the steps given below:

1. Rear Mirror

1.1 Disconnect the SMB-connector of the supply cable from the etalon body.



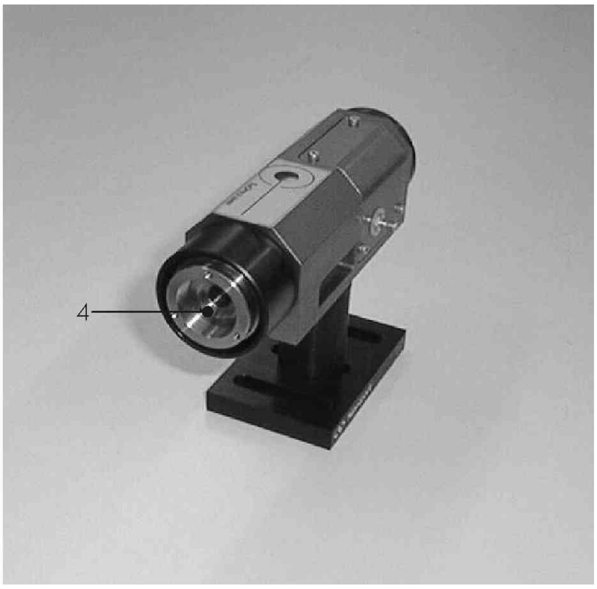


Figure 15 Removing photo detector assembly and rear mirror holder (4)

1.2 Unscrew fastening screws 1-3. Remove the photo detector assembly and the adjusting knob from the resonator adjustment body. This exposes the rear mirror holder (4).

CAUTION !	Do not touch the mirrors as this will degrade their performance. When handling the mirrors always wear gloves.

1.3 Remove the rear mirror holder (4) with the rear mirror by unscrewing it counterclockwise.

1.4 Mount the new rear mirror holder provided by TOPTICA Photonics AG by screwing it into the resonator adjustment body.

NOTE !	If the mirrors are dirty,clean the new set of mirrors by following the procedure described in paragraph 4.5.

1.5 Fasten the photo detector assembly and the adjusting knob with the three fastening screws.

2. Front Mirror

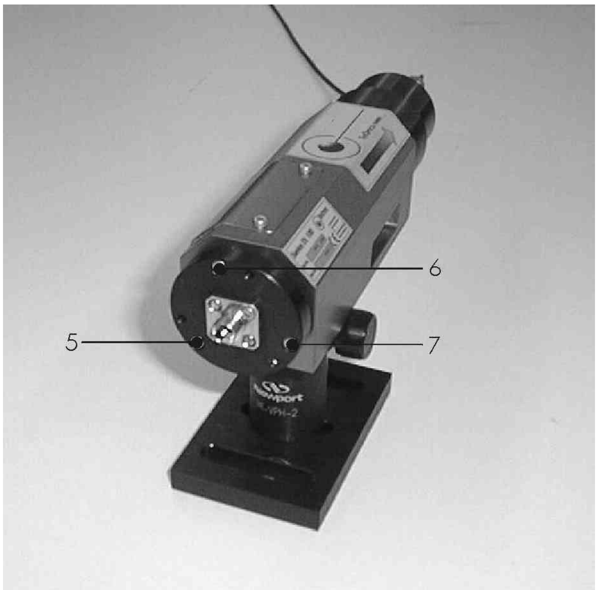


Figure 16 Removing fiber coupling assembly and front mirror holder

2.1 Remove the fiber coupling assembly (or the aperture plate) by unscrewing screws 5 - 7.

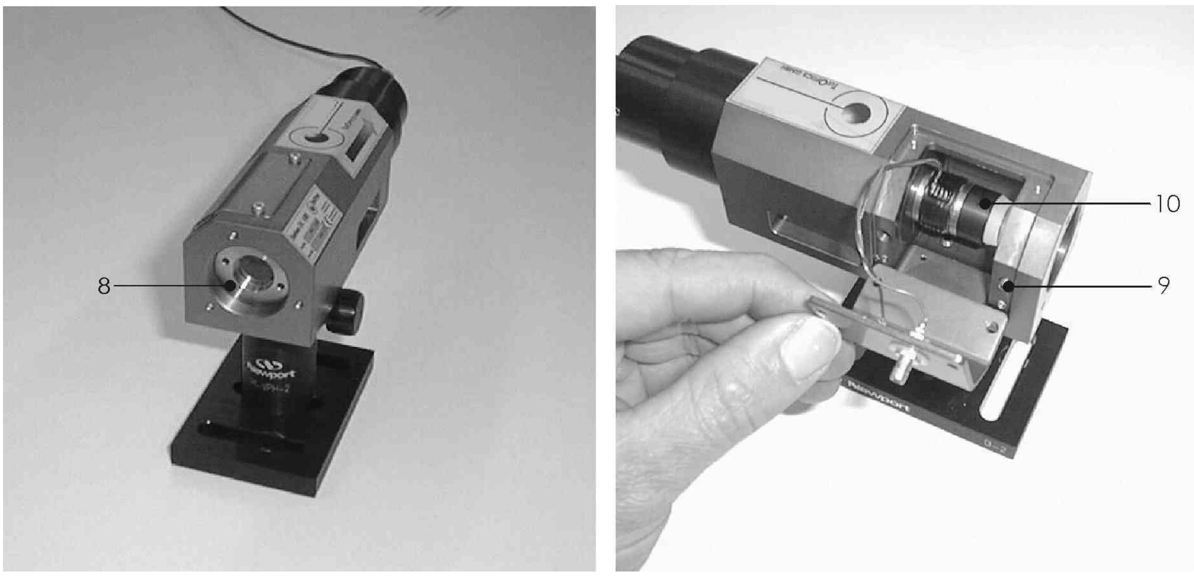


Figure 17 Removing lens holder (8) and front mirror holder (10)

CAUTION !	Do not touch the mirrors as this will degrade their performance. When handling the mirrors always wear gloves.

2.2 Open side cover of FPI 100. Loosen fixing screw (9) and remove lens holder (8). Remove front mirror holder (10) with the front mirror by unscrewing it from the piezo.

2.3 Mount the new front mirror holder provided by TOPTICA Photonics AG by screwing it onto the piezo.

NOTE !	If the mirrors are dirty,clean the new set of mirrors by following the procedure described in paragraph 4.5.

2.4 Check to make sure that your detector and matching lens are appropriate for use with the new mirror set. (see specification tables in paragraph 6.1)

2.5 Screw the lens holder into the etalon body to the position shown in Figure 18 and fix with screw (9).

NOTE !	The position of the lens holder (8) is optimized for collimated laser beams and is independent from the coating of the mirrors.

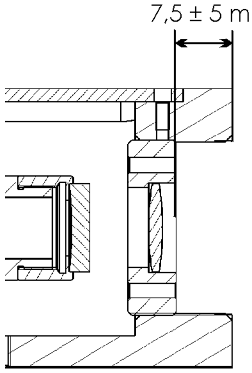


Figure 18 Recommended position of lens holder

2.6 Fix the fiber coupling assembly or aperture plate with the three screws.

NOTE !	It will normaly be necessary to readjust the resonator length after having changed the mirror set due to slight differences of the mirror positions.

4.4.1 Changing free spectral range

The FPI 100 system is designed for a FSR of 1 GHz. It is however also possible to provide a FSR of 4 GHz by changing the mirror sets and the focusing lens.
Please contact TOPTICA Photonics AG for this option.

4.5 Cleaning of mirrors

NOTE !	It is neither necessary nor desirable to clean the mirrors every time they are changed. If stored in their containers and used only in clean environment the mirrors may never need cleaning.

1. Remove both mirrors from the FPI 100. See paragraph 4.4 for instructions. Blow all dust from the coated surface of the mirrors using clean, dry gas.

2. Fold a piece of lens tissue several times to produce a pad 10 - 20 layers thick and approximately the size of the mirrors. Hold the pad in a locking hemostat.

3. Use spectral grade acetone to saturate the pad of lens tissue and then shake the excess off. Repeat this at least twice.

4. Carefully brush the pad of lens tissue across the coated surface of the of one mirror **once** and then discard it. Produce a new pad of lens tissue and clean the other mirror.

5. The mirrrors should now be clean and there should not be a pool of acetone remaining in the center of either mirror. If the mirrors are still dirty, or a pool of acetone has collected on either mirror, repeat the cleaning process.

6. Mount mirrors into FPI 100 according to instructions in paragraph 4.4.

5 Troubleshooting

SYMPTOM	POSSIBLE CAUSES/REMEDIES
Etalon does not scan	Check for defective or damaged electrical connection with the SC 100 or similar ramp generator.
No ramp	The power supply or the PZT may be damaged - call TOPTICA Customer Service. If the ramp signal reappears when the PZT cable is disconnected at the etalon end, there is probably a short in the PZT.
No detector signal	The optical alignment may not be close enough. This is especially true for infrared beams where it is hard to see the beam location. It may be helpful to systematically sweep the translation controls of the etalon mount to search for a signal. Check to see if the beam is retro-reflected from the etalon. The laser power may be to low and the beam size and focus position too far from the optimum to raise the signals above the noise. For weak infrared beams it may be necessary to first align a visible laser to be collinear with the infrared beam and align the FPI 100 with the visible beam. Look for a broken detector lead, improperly installed detector, or incorrect detector. Check the detector functions by removing the detector housing from the adjusting knob and exposing the detector to a light source (room lights, or the source laser beam).
Blown fuse	Call TOPTICA Customer Service.
Low finesse	The laser wavelength my be outside the mirror´s high reflectivity range or the laser linewidth may be to large. Check the transmission curve provided with the etalon mirrors of the spectral range. The photodetector bandwidth may be too low for the ramp generator scan duration or amplitude. Make sure that the photodetector is terminated with 50-1000 Ohm and use a detector amplifier if necessary. The mirrors could be dirty or the coatings may have been damaged. Visually inspect the mirrors for dirt and damage and clean if necessary. If coating damage is suspected, contact the TOPTICA Customer Service Department.
Excessive mode noise, peaks jump randomly	Mechanical vibration coupled to the FPI 100. Remove the source of vibration, isolate FPI 100, and/or tighten the locking screws. The back reflection from the etalon may be causing instability in the source laser. Install an optical isolator or place beamsplitter, neutral density filter, or other optical attenuator in the beam path or tilt the cavity (or laser beam) some degrees away from its initial alignment.

SYMPTOM	POSSIBLE CAUSES/REMEDIES
No sharp transmissions as in Figure 12, only broad featureless signals	The laser beam may not be centered on the coated region of the mirrors and is instead scattering off internal metal parts on the etalon. The laser may have a strong background fluorescence or may be running at a second frequency outside the mirror´s high reflectivity region. One or both mirrors on the etalon are not high reflectors at the laser wavelength. When changing mirror sets, exercise care to prevent inadvertent mixing of mirrors from different spectral ranges. Once the mirrors are mixed the only recourse may be to check transmission spectra with a spectrometer and then rematch appropriate pairs. Visual color differences in mirror reflectivity are also good clues in matching mirror pairs.
Excessive low frequency noise obscuring signal	Mechanical vibrations may be causing apparent frequency jitter of the signal. The mirrors could be loose and subject to vibration; check for secure mounting. The PZT may be damaged due to impact or excessive voltage - call TOPTICA Customer Service. Photodetector may be defective - Call TOPTICA Customer Service.
Excessive high frequency noise obscuring signal	Look for a possible ground loop to other electronics through the base of the unit and the optical table. Isolate the FPI 100 from the table as necessary.
Excessive thermal drift	Shield the etalon assembly from temperature variations. The FPI 100 is designed for a temperature stabilization. Refer to TOPTICA Customer Service.

6 Appendix

6.1 Specifications

Interferometer Specifications

Cavity Design:	Confocal spherical mirrors
FSR:	1 GHz or 4 GHz
Finesse:	>100 over specified wavelength range (>300 by request)
Coating Ranges Available:	380 to 1700 nm
Input Clear Aperture:	5 mm
Dimensions:	174,5 x 40 x 46,6 mm
Etalon Body:	Aluminium and PZT cavity construction
Adjusting Knob	POM
Thermal Sensitivity:	7µm/°C
Minimum Input Power:	10 µW bei 633 nm, Amplitude = 200 mV

PZT Specifications

Piezoelectric Scan:	1µm/100 Volt
PZT Capacitance:	50 nF
PZT Maximum Voltage:	500 Volt

Mode Matching Lens

Type:	biconvex
Focal Distance f:	50 mm for FSR 1 GHz (30 mm for FSR 4 GHz)
AR Coating:	None (only on request)

	Matching Lens	Radius of Mirror
FSR 1 GHz	f = 50 mm	75 mm
FSR 4 GHz	f = 30 mm	18.75 mm

Fiber Coupler Lens

Type:	Multilens
Focal Distance:	4.5 mm
Numerical Aperture:	0.47
AR Coatings:	@ 630, 780 and 1400 nm

Photodetectors

λ [nm]	Detector
380 - 1000	Si-Detector
1000 - 1700	InGaAs-Detector

6.2 Main Dimensions of FPI 100

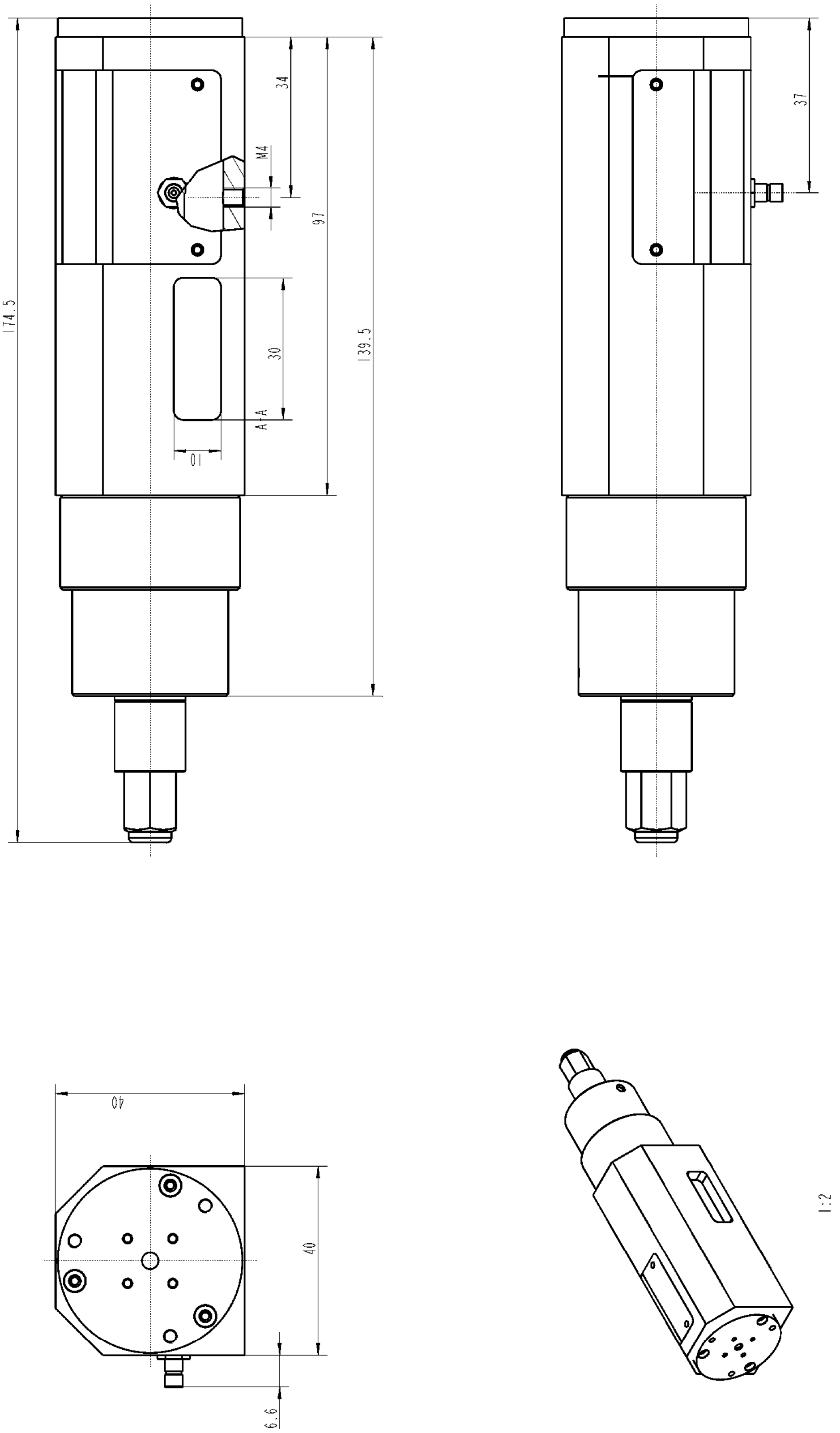


Figure 19 FPI 100 Main Dimensions

6.3 Modes of a Spherical Mirror Interferometer

The general expression for the modal frequencies of spherical mirror interferometers was derived by Boyd and Kogelnick[1] as

$$\nu = \frac{c}{2d}\left[q + \frac{1}{\pi}(1 + m + n)\cos^{-1}\left(1 - \frac{d}{r}\right)\right]$$

In this expression *q*, *m*, and *n* are positive integers, where *q* refers to the axial mode number; *m* and *n* refer to transverse modes. For plane mirrors the radius is infinite; while for confocal systems $r = d$. Thus the resonance frequencies are multiples of $c/2d$ for the plane case, and $c/4d$ for the confocal.

When $r = d$, the confocal condition, all the odd modes are degenerate and distinct from all the even modes, which are also degenerate. Furthermore, the even modes overlap the axial modes, while the odd modes transmit exactly half way between. This situation is termed a mode-degenerate interferometer and is a very useful configuration since if the incoming laser excites higher order transverse modes, the only penalty is that the FSR is halved but the interferometer has no spurious transmissions. This is the normal operating mode of the FPI 100.

When $r \neq d$, as is the case during alignment of the mirror spacing in the etalon, additional modes will appear since it is not mode-degenerate. Here even a single frequency input will produce a multiple peak transmission signal unless the higher order transverse modes are not excited. Excitation of only the lowest order transverse modes (*m* and *n* both equal to zero) is called mode-matching and produces a transmission with a FSR equal to the plane mirror value of $c/2d$ for any values of *r* and *d*.

6.4 Finesse

The mirror finesse of the FPI 100 Interferometer may be partitioned into contributions from reflectivity (F_R) and surface imperfections (F_S). The overall instrument finesse (F_I) is determined by the parallel combination of these terms through the relation.

$$F_I^{-2} = F_R^{-2} + F_S^{-2}$$

The reflectivity finesse is determined by the mirror reflectivity (R) according to

$$F_R = \frac{\pi R}{(1 - R^2)^{\frac{1}{2}}}$$

This relation is valid for a non mode-matched confocal system. For either plane mirrors or for mode-matched curved mirrors of any radius F_R is approximately twice the value given by the above formula.

In order to have a finesse of 300, it is therefore necessary to have a reflectivity of al least 99.5%. This value is far below the maximum attainable for state of the art coatings, for which reflectivities of 99.99% are possible. Since reflectivity is not the sole determinant of finesse, it is obvious that there is an optimum reflectivity which is less than the maximum in cases where the surface finesse is not infinite.

The surface finesse is a measure of how closely the mirror substrate approximates the ideal geometric spherical segment. On a microscopic scale surface roughness implies that the optical distance between the mirrors is not constant for adjacent regions of the mirror surface. From the resonance condition this means that there will be a distribution of transmissions centered about the mean. Such a spread is equiv-

1. G.D. Boyd and H. Kogelnick, *Bell Syst. Tech. J.* **41**:1347 (1962)

alent to a broadened transmission or a reduced finesse. With standard polishing techniques, surface roughness of 20 Å is achievable while for so-called super polishing methods this value may be reduced by an order of magnitude. The surface finesse implied by these roughness values varies between 10^4 and 10^5. Consequently, super polishing is unnecessary for an instrument finesse in the neighborhood of 10^3, but is essential for one in excess of 10^4.

Another potential complication of using a too high reflectivity is reduced instrument transmission (T). As reflectivity increases, the mirror losses due to absorption and scattering become amplified and the instrument transmission decreases according to the equation for a confocal interferometer,

$$T = \frac{1}{2}\left(1 - \frac{A}{1-R}\right)^2$$

where *A* is the sum of the absorption and scattering losses.

Standard optical coatings can have losses in the range of 200 to 1000 ppm, while the best state of the art coatings have losses as low as 20 ppm. Unfortunately, such super coatings are expensive and are not available in all spectral ranges.

The FPI 100 mirrors generally use reflectivities of about 99.7% to achieve a finesse in excess of 300 and a transmission of greater than 10%. These mirrors are available in virtually every spectral range. While higher reflectivities may be used without problem in the FPI 100 etalon, the transmission will begin to decrease and the finesse will not increase as rapidly as one approaches limits set by mirror absorption and substrate polishing.