Scanning confocal cavity SCC-XXX
of a Fabry-Perot type

Technical description
and instruction manual.

Moscow 2005.

1. Function.

Confocal cavity often referred as a spherical Fabry-Perot is a high-Q optical resonator. It consists of two mirrors having the same curvature and separated by the distance **L** equal to their radii of curvature **r** (Fig.1). The spherical Fabry-Perot cavities play a particular role in laser physics: first, as high-resolution spectrum analyzers for the specification of laser mode structure and for the measuring of laser linewidth; and second, as laser resonators. In general, the confocal cavities ensure more high spectral resolution than the conventional Fabry-Perot cavities with the flat mirrors because the misalignment of spherical mirrors, unlike the flat ones, does not lead in the first order to the change of an optical path, which is equal **4r** (Fig.2). Besides, the spherical mirrors can be polished with a much higher quality, that is to say the deviation of such mirrors from an ideal sphere is smaller than the deviation of the flat mirrors from an ideal plane.

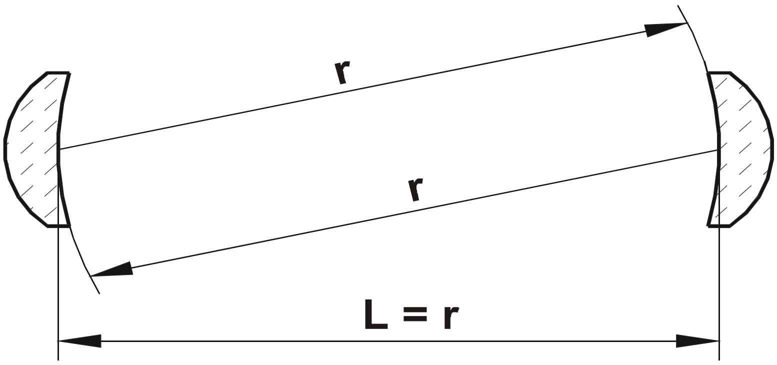


Fig.1. The curvature and the mutual position of mirrors in a confocal optical scheme.

These conditions determine the choice of a confocal scheme for the cavities of SCC-XXX type, which are designed to analyze the fine structure of an optical spectrum and to measure the laser linewidth.

2. Notions and technical data.

Figure 2 shows the interpretation in approximation of geometric optics how the transmission resonance of a confocal cavity is formed. The laser beam entering the cavity parallel to the optical axis at the point $\mathbf{P_1}$ is reflected in series at the points $\mathbf{P_2}$, $\mathbf{P_3}$, and $\mathbf{P_4}$ passing twice the focal point **F** and interferes with itself at $\mathbf{P_1}$. The higher reflection coefficient of mirrors the bigger number of partial waves takes part in interference and, consequently, the higher spectral resolution of the device. It is evidently from the picture that the total round trip of the cavity (i.e. minimal path providing multi beam interference) equals **4r=4L**.

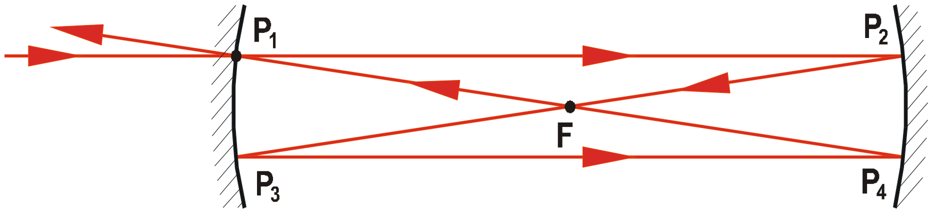


Fig.2. Ray traces in a confocal cavity in the approximation of geometric optics.

Thus, the free spectrum range FSR (the frequency interval between the neighboring peaks of constructive interference) of such an interferometer equals:

$$\text{FSR} = \frac{c}{4\text{L}}, \qquad (1)$$

where c – speed of light, L – distance between mirrors. For example, confocal Fabry-Perot cavity SCC-750 has a cavity length of 100 mm, which corresponds to FSR=750 MHz. The $\mathbf{P_i}$ points are the exit ports of the optical radiation stored in the cavity.

It should be noted that the total round trip is equal 2L at the careful spatial matching of the input radiation and the fundamental transversal mode of a spherical resonator (pairs of points $\mathbf{P_1}$ – $\mathbf{P_3}$ and $\mathbf{P_2}$ – $\mathbf{P_4}$ degenerate in one point). In such case the free spectrum range is described by the same formula as for the conventional flat Fabry-Perot cavity:

$$\text{FSR} = \frac{c}{2\text{L}}. \qquad (2)$$

This means, that in observed optical signal the peaks of transmission corresponding to the spatial modes with the odd indices (for example, TEM_{01} or TEM_{11}) are absent or greatly suppressed. It is quite difficult to realize this case in practice because it is very sensitive to the alignment of the input beam (its direction and diameter). At the same time this case can be easily separated from the case described by the formula (1) by the gentle displacement of the analyzed beam from the optical axis.

The parameter describing the quality of a cavity and its mirrors is *finesse*. It is expressed by the ratio of the free spectrum range and the width (full width at half-maximum FWHM) of the transmission resonance Δν:

$$finesse = \frac{\text{FSR}}{\Delta\nu}. \qquad (3)$$

For the case of the flat Fabry-Perot cavity the finesse is related with the reflection coefficient by the formula:

$$finesse = \frac{\pi\sqrt{R}}{1-R}, \tag{4}$$

where R – the reflection coefficient of the cavity mirrors.

For the case depicted on Fig.2 and satisfied the formula (1) the finesse is modified:

$$finesse = \frac{\pi R}{1-R^2}, \tag{5}$$

i.e. it is practically half as much than according the formula (4).

The finesse of SCC series interferometers is individually measured for each specimen with the use of the extended cavity diode laser having the linewidth below 1 MHz. This linewidth is comparable with the resolution of high-Q cavities (SCC-250 type) and might introduce a certain error in $\Delta\nu$ determination.

Cavity type	**SCC-2500**	**SCC-750**	**SCC-250**
Cavity length	**30 mm**	**100 mm**	**300 mm**
Free spectrum range	**2.5 GHz**	**750 MHz**	**250 MHz**
Finesse	**150**	**150**	**150**
Resolution	**16 MHz**	**5 MHz**	**1.6 MHz**
Waist diameter of the TEM_{00} mode (at 852 nm)	**130 µm**	**230 µm**	**400 µm**
Dimensions	**Ø 27 × 54 mm**	**Ø 27 × 117 mm**	**Ø 28 × 318 mm**
Translation range of the movable mirror	**1.5 µm**	**1.5 µm**	**1.5 µm**
Sensitivity of the translation on PZT voltage	**3.5 nm/V**	**3.5 nm/V**	**3.5 nm/V**
Sensitivity of the eigen mode frequency on PZT voltage	**40 MHz/V**	**12 MHz/V**	**4 MHz/V**

Table 1. The main technical parameters of SCC type cavities.

To get the optical signal of the ultimate amplitude and of the minimal width it is useful to know waist diameter of the TEM_{00} mode of the particular cavity. This facilitates the spatial mode matching of the cavity and laser modes or, at least, simplifies the choice of the diaphragm, which can limit the number of the excited cavity modes. Generally, the quite efficient coupling of the parallel light beam into the spherical Fabry-Perot cavity can be provided with the use of a lens, which focus the beam into the midpoint of the cavity. The waist size (its radius) ω_0 depends on the radiation wavelength λ and the radius of mirrors r:

$$\omega_0 = \sqrt{\frac{\lambda r}{2\pi}}. \tag{6}$$

For the wavelength 852 nm and the mirror radii of 300 mm the waist diameter $2\omega_0$ is 400 micrometers.

The technical data of the SCC type cavities are presented in table 1.

3. Structure and operation of the scanning confocal cavity.

3.1. The optical part. The top view of the optical set-up used to measure laser linewidth is shown on the figure 3. The main components of the set-up are figured: the scanning confocal cavity SCC-250 (1) with its connector (2), an optical Faraday isolator (3), a diaphragm (4), a Fresnel rhomb (5), coupling mirrors in their aligning mounts (6).

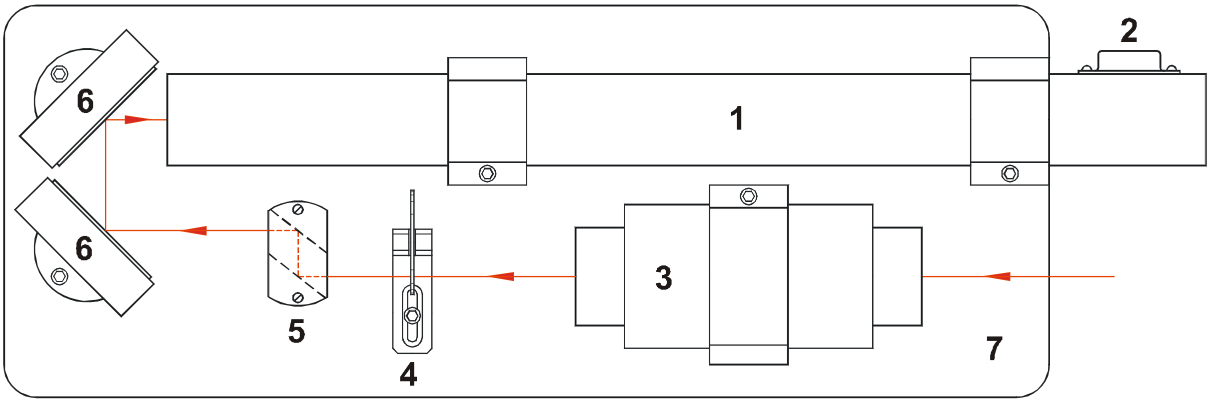


Fig.3. The top view of the set-up for the laser linewidth test.
1 – scanning confocal cavity SCC-250, 2 – connector of SCC with its driver, 3 – optical Faraday isolator, 4 – diaphragm, 5 – Fresnel rhomb, 6 – aluminum coupling mirrors.

To measure the laser linewidth the beam of the testing laser (the beam direction is labeled by arrows on Fig.3) has to be sent into the cavity along its optical axis. The transmitted optical power is registered by photodiode, which is mounted in one module with the cavity mirrors (Fig.4, position 10). One of the mirrors (Fig.4, pos.1, 2) can be translated by the piezo-transducer (Fig.4, pos.3) changing by that the cavity length. Since the voltage applied to the PZT varies linearly, the cavity length and the eigen mode frequency also change linearly.

When the optical frequency of a certain cavity mode coincides with the frequency of analyzed radiation, the light passes the mirrors and hits the photodiode. Thus, one can observe the transmitting peaks at the scanning regime of SCC (Fig.5). The shape of the separate resonance is a convolution of the cavity and laser lines. If both initial lines are Lorentzian then the resulting contour is also Lorentzian with the half-width (full width at half maximum, FWHM) equal to the sum their half-widths. This means that the linewidth measurement with the use of a scanning confocal cavity gives the upper-bound estimate, and it is more accurate if the cavity line is narrower.

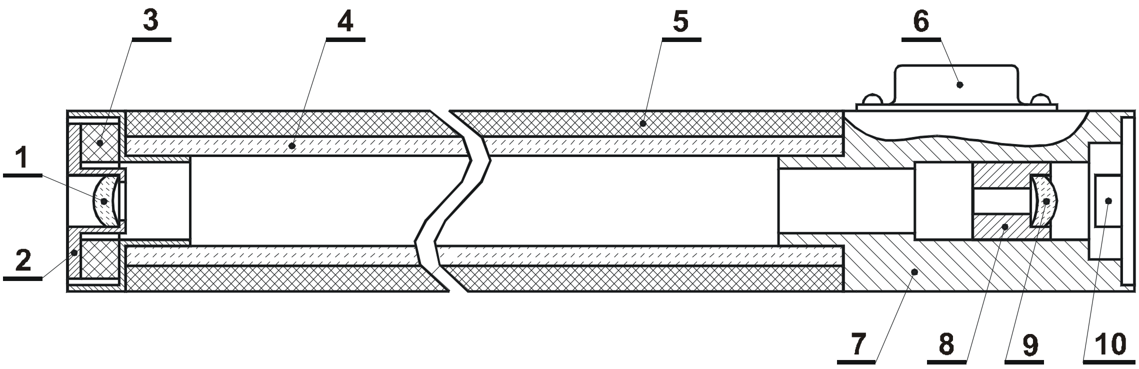


Fig.4. Structure of a scanning confocal cavity SCC-250.
1 – moving mirror, 2 – mount of the moving mirror, 3 – piezo transducer, 4 – fused silica spacer, 5 – insulating coating, 6 – connector, 7 – body, 8 – mount of the adjustable mirror, 9 – adjustable mirror, 10 – photodiode.

Destructive reflection from the cavity is able to affect the regime of laser operation and, consequently, to change the spectral parameters of the laser. To correct such perturbations of the laser spectrum the optical isolator has to be employed in the set-up for the laser linewidth test. The higher isolation provides more precise measurements. The double stage optical isolator is utilized to qualify the SCC type cavities. The first stage is an optical Faraday isolator. The principle of its operation based on the fact that the polarization plane of the linearly polarized light is rotated on propagation in magneto-optical crystal placed in a magnetic field. The direction and the magnitude of the rotation do not depend on the direction of light propagation. If the length of a magneto-optical crystal and the magnetic field magnitude are selected to rotate the plane of polarization on 45°, then the total angle of rotation amounts to 90° on the propagation back and forth. Thus, a polarizer can block the backward beam. Two polarizers are utilized in the Faraday optical isolator. The input polarizer blocks the reflected wave, while the output polarizer ensures efficient isolation even when the polarization of the backward wave differs from linear. Typically the isolation of the commercial Faraday isolators is in the range of 32÷38 dB. Often this is not enough, especially for the work with the diode lasers, which are extremely sensitive to any kind of optical feedback. So the second stage of isolation enhances the overall performance of the set-up.

The second stage of optical isolation provides additionally more than 15 dB. It consists of the Fresnel rhomb (Fig.3, pos.5) and the output polarizer of the Faraday isolator. The plane of polarization at the output of the Faraday isolator is oriented in respect to the Fresnel rhomb in such a way, that the rhomb plays the role of quarter-wave phase plate, i.e. linearly polarized light gets circularly polarized on propagation through the rhomb. The reflected from the cavity wave passing the Fresnel rhomb in backward direction gets linear polarized again, but its plane of polarization is orthogonal to the one of the direct wave, and thereby the backward beam is blocked by the polarizer. The disadvantage of such a way to suppress parasitic reflections from the cavity is its high sensitivity to degree of polarization. Spoilt circular polarization seriously reduces the optical isolation. That is why the metal mirrors only (Fig. 3, pos.6) are used in the set-up, since they affect polarization less than dielectric ones.

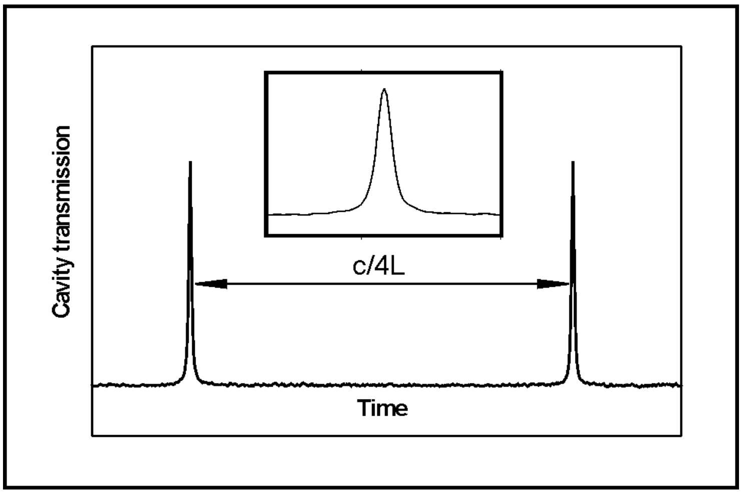


Fig.5. The transmission peaks of scanning confocal cavity and the line shape of the individual resonance (on insert).

To simplify the entering of light into the cavity the mirror substrates of SCC-750 and SCC-250 are made alike a meniscus positive lens as it is shown on figures 1 and 4. The focuses of the lenses and the mirrors coincide together providing reasonable mode matching for the beams of small diameter (~1 mm). The beams of bigger diameter still need an additional lens. The set of diaphragms (Fig.3, pos.4) may help to find the optimum between the amplitude of the observed signal and the degree of spatial filtering of analyzed radiation. The diaphragm size is considered as optimal when the substitution of the diaphragm by the smaller one does not change the width of the observed transmission resonance.

3.2. Scanning cavity driver CFPD200. The CFPD200 controls piezo-elements of a scanning Fabry-Perot cavity, converts photo current into voltage, and provides differential output of two independent inputs. There are three fuse sockets under the unit lid close to the line connector. One socket corresponds to the line voltage of 240V AC, another one – to the voltage of 220V AC, and third one – to the voltage of 110V AC. **Only one fuse of 0.5A must**

be inserted into the relevant socket! An additional fuse (F1, see printing board outline) of 160 mA protects the output of a high-voltage stabilizer from the shortening.

The front and rear panels of the electronic unit are shown on the Fig.6. The front panel is divided onto few functional zones reflecting operation of the CFPD200. The zone INPUT includes two BNC connectors (INPUT1, INPUT2) and two trimmers, which allow adjusting the amplitudes of the input signals. The differential signal of two inputs can be monitored from the BNC connector (DIFFERENTIAL) in the OUTPUT zone.

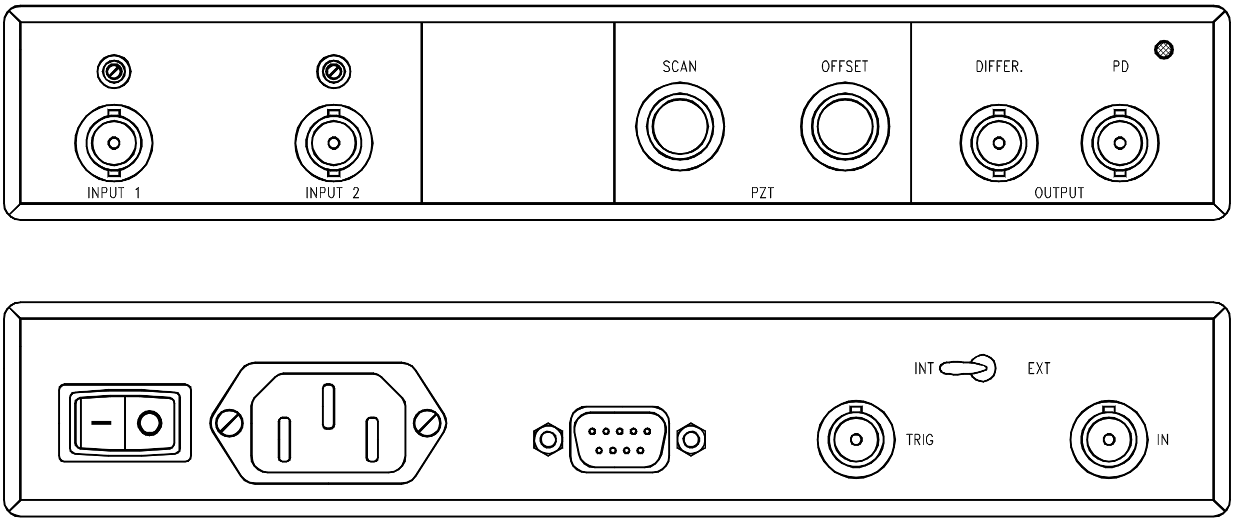


Fig.6. The front and rear panels of the CFPD200.

The PZT zone includes two knobs controlling a high-voltage amplifier. The left one (SCAN) regulates the amplitude of AC component at the amplifier output, and the right one (OFFSET) sets the DC level. The maximum output voltage of the high-voltage amplifier is about 200V and it has two outputs (HV1 and HV2 of DRB-9F) opposite in phase. So, the piezo-element being connected between both outputs might suffer the voltage change from -200V to +200V. The maximum PZT tuning is obtained at the neutral position of the OFFSET knob.

The OUTPUT zone also includes the output of the converter (BNC-connector PD), which transforms the current of a photodiode into the voltage. The switch SW12 disposed on the printing board can change the coefficient of transformation. The cathode of the photodiode must be connected to the pin 5 of DRB-9F, and the anode to the pin 4.

The light emitting diode in the OUTPUT zone indicates when the power is on.

The CFPD200 has an internal triangular-wave generator. It can modulate the PZT voltage at the line frequency and its sub-harmonics **f**, **f/2**, **f/4**, **f/8**. The constant phase difference between the signal of an internal oscillator and a line frequency allows minimizing the influence of line pickup under optical data recording. To set sweep frequency, only one corresponding jumper of the DIP-8 switch on the printing board (SW14) must be set in position ON. The built-in generator can be disconnected from the high-voltage amplifier by the EXT-INT switch disposed on the rear panel of the CFPD200.

The power switch, the line connector, the scanning cavity connector (DRB-9F), the connector IN of an external signal, the switch of a control signal (EXT-INT), and the connector TRIG of the built-in generator are assembled on the rear panel. The triangular signal of about $3V_{p-p}$ from the TRIG output can be used to control or to synchronize external devices. In order to control the high-voltage output of the CFPD200 by an external signal the EXT-INT switch must be set into the EXT position. In this case the output of the built-in sweep generator is disconnected from the input of the high-voltage amplifier.
сигнал внешнего управления подается на расположенный рядом разъем IN.

4. General prescription on maintenance.

The scanning confocal cavity is a fragile optical device, which needs accurate handling during transportation, storing, and operation. It is necessary to fulfil following requirements for reliable operation of the cavity:

– avoid shocks and impacts,
– prevent the cavity from the abrupt temperature fluctuations, moisture, and condensate water on the optical surfaces,
– shut out dismantling of the cavity,
– exclude connection of SCC-XXX to another cavity controllers,
– exclude the operation of the cavity driver without protective grounding (it is enabled through the central contact of power cord),
– remember that the piezo-elements are supplied by the voltage up to 240 V.

5. Preliminaries.

To measure the laser linewidth one needs an oscilloscope with the registration bandwidth of at least 10 MHz in addition to the optical part and the cavity driver (see chapter 3 of this manual). It is preferable to use a storage oscilloscope, since it simplifies readout of measured intervals.

The optical part has to be assembled on a horizontal, plane, and stable surface excluding vibrations of the cavity. The scanning cavity driver is connected to the power line with indispensable grounding of mid contact piece of a power cord.

The output PD of the cavity driver CFPD200 is connected to the main input of the oscilloscope. The oscilloscope having triggering from the power line can be synchronized internally, since the frequencies of the driver's sweep generator and of the power line have rigid phase relations. However, if the triggering is absent, not stable, or over frequent then use an external synchronization. In this case the output TRIG of CFPD200 has to be connected to the external triggering input of the oscilloscope.

Insert the cable connecting SCC and CFPD200 into the cavity connector gently, avoiding skewing and strong tension, holding the body of the cavity by hand. The maximum precautions are needed for the SCC-250, for which it is intolerably to strain the body (Fig.4, pos.7) in respect to the fused silica spacer (Fig.4, pos.4), since the last one may be broken.

The warm up time of the confocal cavity driver CFPD200 is about 5-10 minutes. After that time the drifts of the output voltage, the sweep amplitude, and consequently of the cavity length and the eigen mode frequencies are dropped off.

The beam of the tested laser is directed along the optical axis of the cavity providing the maximum magnitude of transmission peaks. The observed peaks should be symmetrical and without steps and deformations which may indicate the presence of destructive optical feedback (see Fig.5). Such distortions may be nipped with the use of an optical isolator or even by an optical filter placed at the output of the laser. The filter reduces the observed signal according its transmission, however the power in the feedback wave is reduced as squared transmission.

6. Measuring procedure.

The comb of the cavity eigen modes produces frequency scale for the half-width measurements of a transmission peak. The frequency separation of two neighboring peaks equals to the free spectrum range of the cavity (i.e. 2.5 GHz for SCC-2500, 750 MHz for SCC-750, and 250 MHz for SCC-250). The linear scanning of the cavity length consents at the half-width determination to substitute the frequency distance between the cavity modes by the time intervals between the moments of observation of the transmission maximums.

The measurement of the full width of the cavity transmission peak at the half of its intensity realizes the definition of the laser linewidth.

Make sure before readout the time intervals, that the observed transmission resonances are really neighboring, that is they are located on the same slope of the piezo scan and they are not the same resonance recorded on the way back and forth of the scan. The transmission peaks are neighboring if they move to one side when the knob OFFSET is rotated. If they move in opposite directions, then this is the same resonance recorded twice.

The reading of intervals for the neighboring peaks and for the half-width of the individual peak must be performed at the same position of the knob SCAN. It is allowed to shift the transmission resonance by the knob OFFSET for more practical readout.

The measuring example. The time interval between two neighboring peaks (as it is shown on Fig.5) amounts 8 boxes of an oscilloscope display at the sweep of 2 ms/box. Thereby the free spectrum range (say 750 MHz) corresponds to the interval of 16 ms.

Perform the reading of the time interval corresponding to the half-width of the peak. Reduce the sweep time of oscilloscope to enhance accuracy of readout (as it is shown on insert of Fig. 5). At the sweep time of 100 μs/box the half-width equals 3.2 boxes, i.e. 0.32 ms.

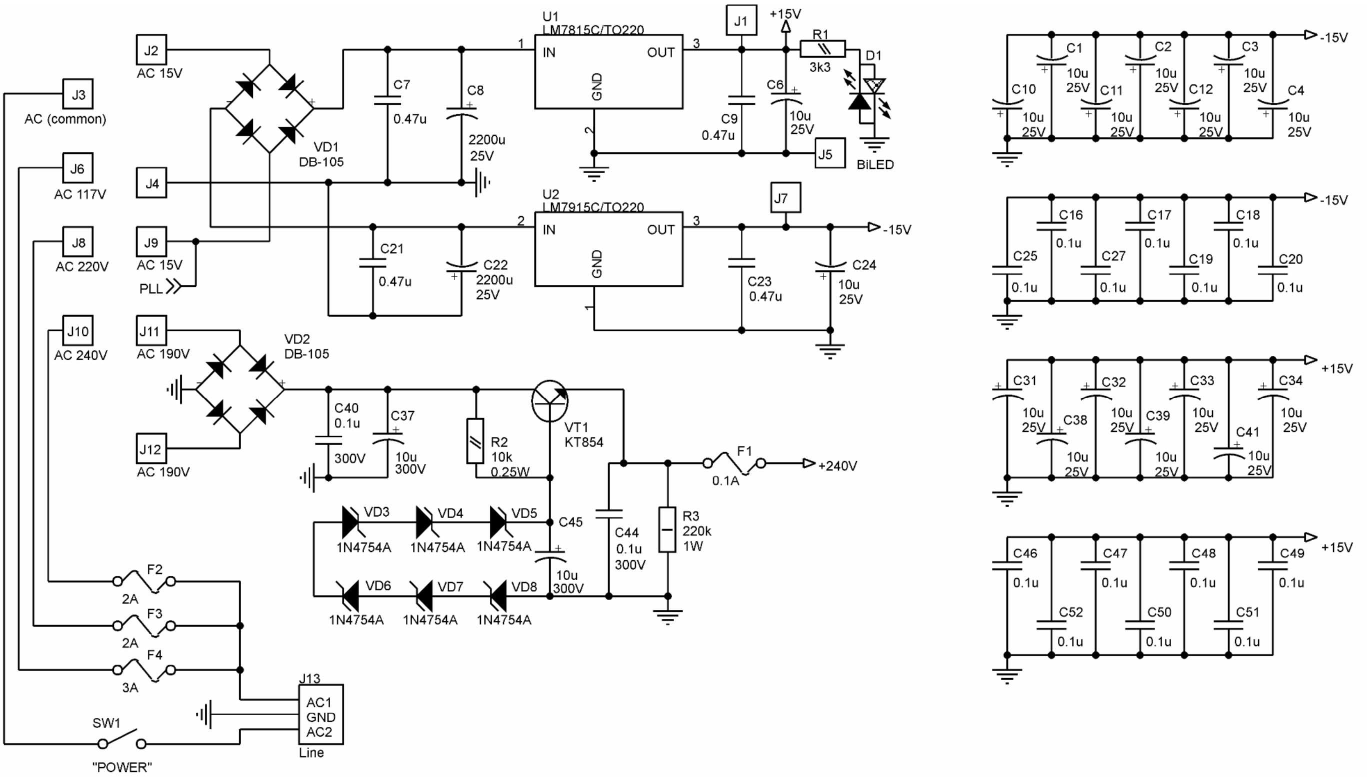
It is necessary to correct the measured half-width of the observed resonance for the resolution of the cavity. As a result:

$$\text{laser linewidth} = 750MHz \times \frac{0.32ms}{16ms} - 5MHz = 10MHz\,.$$

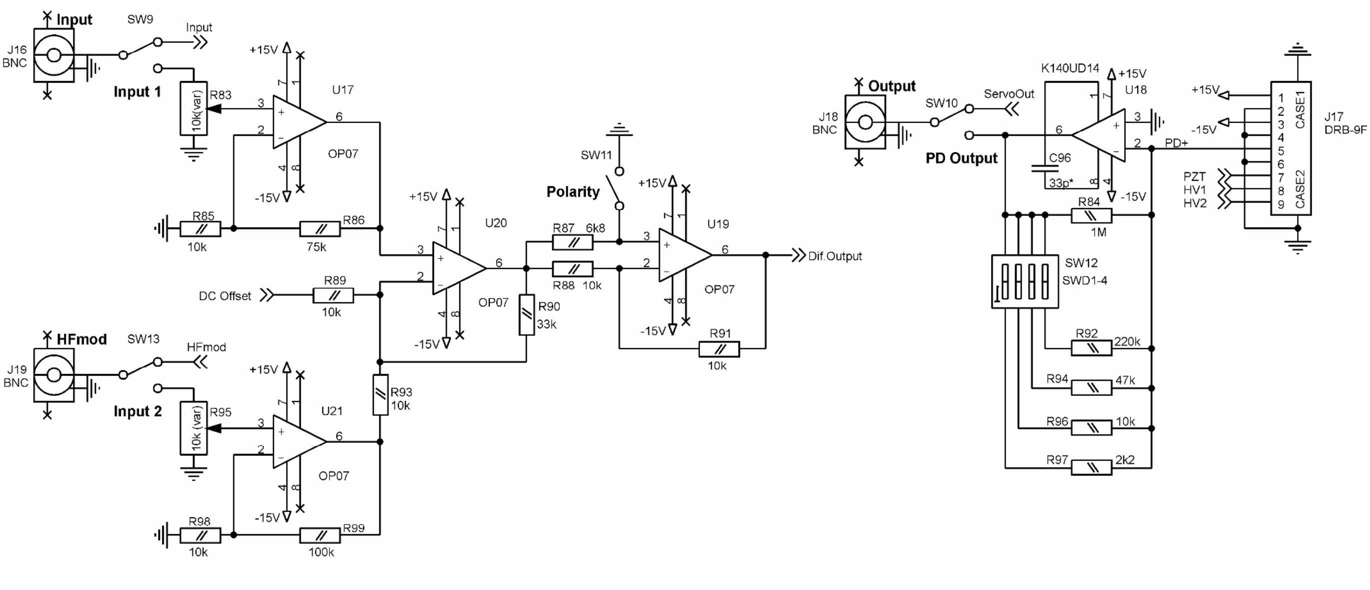
7. Typical failures and their repair.

	Failure character	Origin of failure	Repairing means
1	The indicating LED on the front panel does not light at the switching the driver on.	The power fuse has blown.	Replace the line fuse.
2	Oscilloscope is connected to the output TRIG, but is not synchronized.	The EXT-INT switch is in EXT position.	The EXT-INT switch set in position INT.
3	The indicating LED lights, but PZT is not scanned.	The EXT-INT switch is in EXT position.	The EXT-INT switch set in position INT.
4	The indicating LED lights, but PZT is not scanned.	The high voltage is absent.	Replace the fuse of the high-voltage power supply.
5	PZT is not scanned, the fuse of the high-voltage power supply blows immediately after the turning the driver on.	High-voltage amplifier TDA6101Q has burned.	Replace high-voltage amplifier TDA6101Q.
6	The output of the internal triangular-wave generator fluctuates in a random way.	Poor quality of the mains voltage.	Drop the sweep frequency by the switch SW14.
7	The fluctuations at the output of the triangular-wave generator occur too often, and changeover to the lower frequency does not help.	Very bad quality of the mains voltage.	Use an external generator or an AC stabilizer of supply-line voltage.
8	The signal at the PD output is weak, low contrast, has large DC pedestal.	The tested laser has a multimode structure.	Reject the laser according requirements.

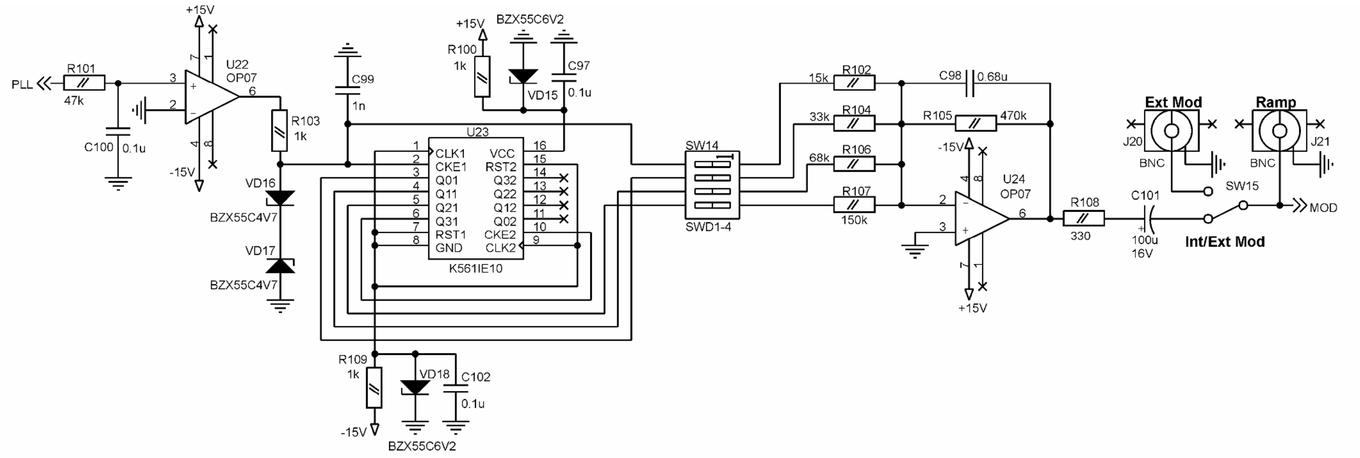
Appendix: electrical schematic diagrams and wiring layouts of CFPD200 sub-modules.



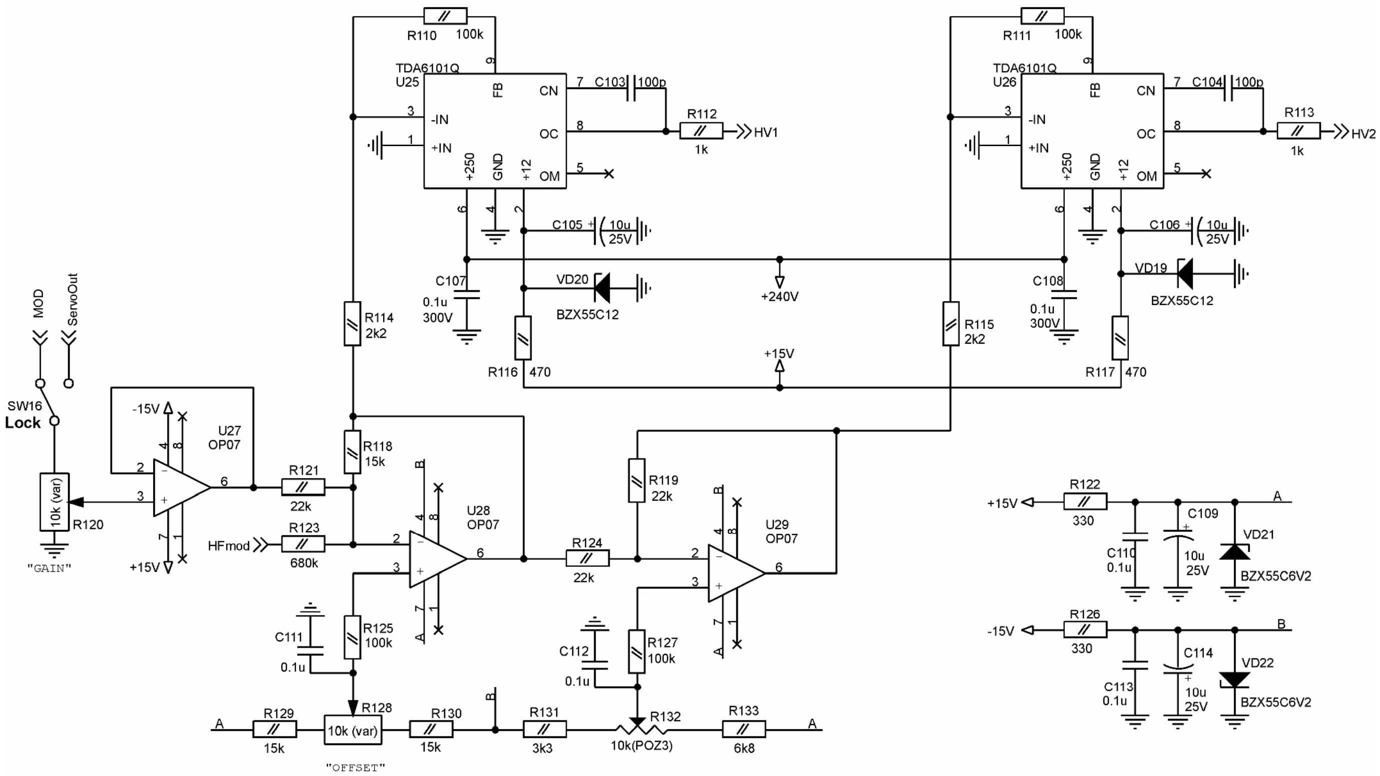
Power supply of Universal Frequency Lock



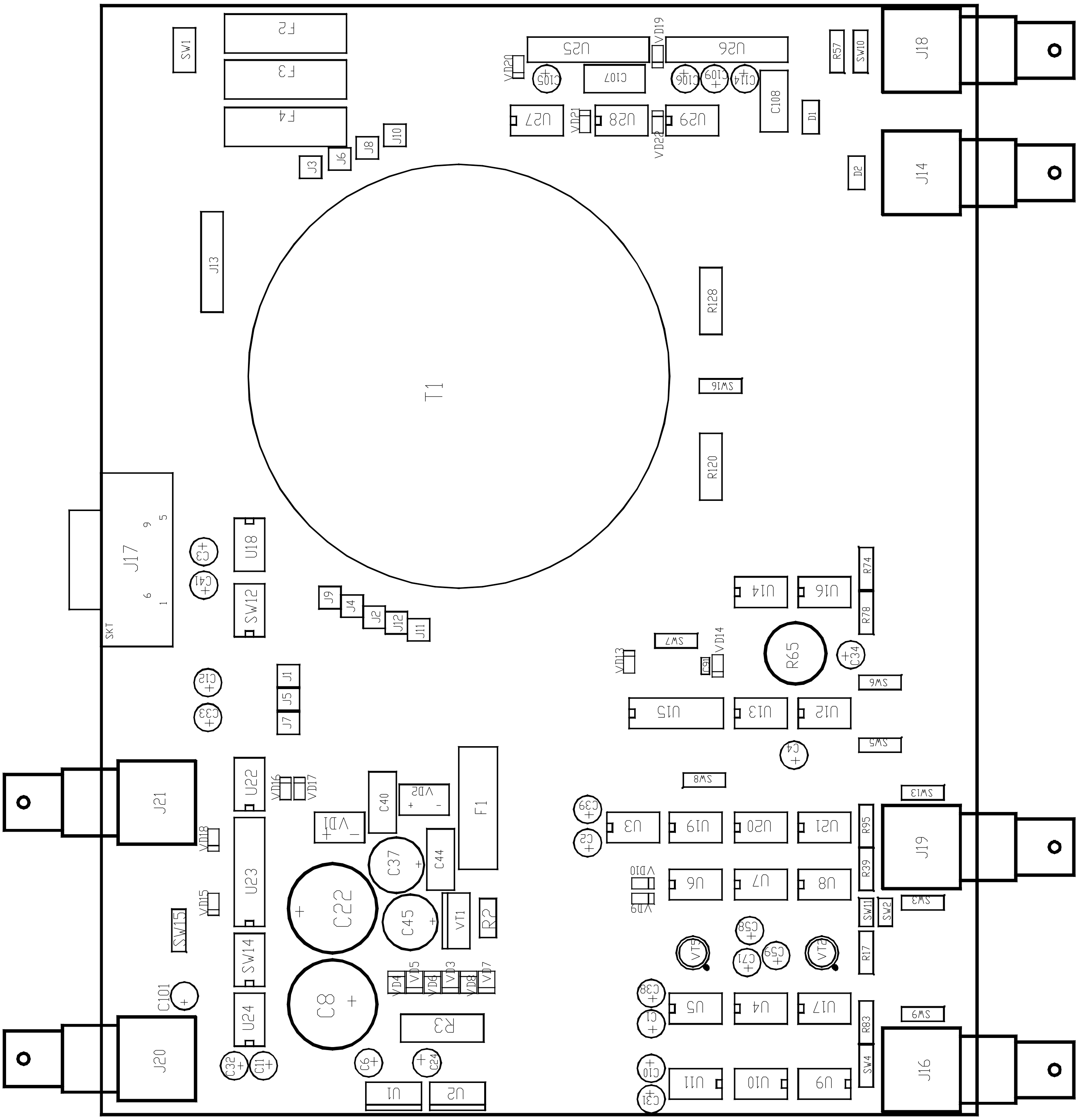
Differential input & Photodiode amplifier

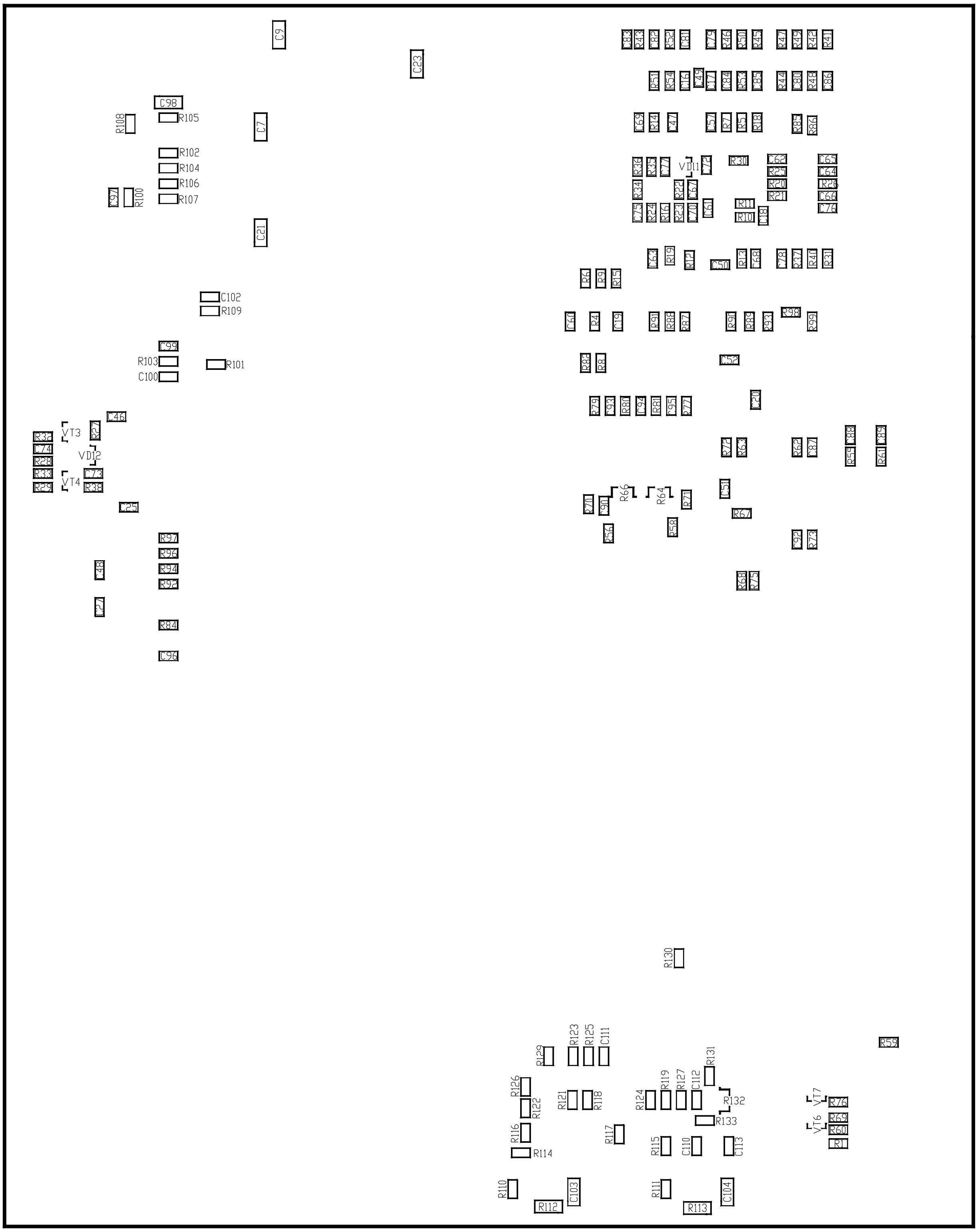


Generator



High-voltage amplifier


SW1
F2
F3
F4
U25
VD19
U26
VD20
C105
C107
C106
C109
C114
R57
SW10
J18
C108
D1
U27
VD21
U28
VD22
U29
J10
J8
J6
J3
D2
J14
J13
T1
R128
SW16
R120
J17
SKT
C3
C41
U18
SW12
J9
J4
J2
J12
J11
R74
U14
U16
R78
SW7
VD14
VD13
R65
C34
C12
J1
J5
J7
C33
SW6
U15
U13
U12
SW5
C4
J21
U22
VD16
VD17
C40
VD2
F1
SW8
SW13
C39
U3
U19
U20
U21
R95
J19
VD1
C2
VD18
U23
C37
C44
C22
VD10
U6
U7
U8
R39
VD9
SW11
SW2
SW3
VD15
C45
VT1
R2
SW15
C58
C71
C59
R17
SW14
VD4
VD5
VD6
VD3
VD8
VD7
C101
C8
C38
U5
U4
U17
R83
SW9
C1
J20
U24
R3
SW4
J16
C32
C11
C6
C24
C10
U11
U10
U9
U1
U2
C31


C9
C23
C98
R108
R105
C7
R102
R104
R106
R107
R100
C21
C102
R109
C99
R103
R101
C100
C46
VT3
VD12
VT4
C73
R38
C25
R97
R96
R94
R92
R84
C96
VD11
R30
R11
R10
C50
C52
R66
R64
R67
R130
R129
R123
R125
C111
R131
R126
R122
R121
R118
R124
R119
R127
C112
R132
R133
R116
R114
R117
R115
C110
C113
R110
R112
C103
R111
R113
C104
R59
VT7
VT6
R76
R69
R60
R1