# Terahertz beam guiding in a spectrometer with photoconductive antennas

## PCA – photoconductive antenna

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The beam profile in a terahertz time-domain spectrometer (TDS) must be adjusted according to the needs given bei the sample geometry. In general a parallel beam with a small beam diameter would be the ideal situation, but in case of THz waves with wavelength in the range between 100 µm and 3 mm the diffraction on the lens aperture is significant. Therefore a compromise between a small beam diameter and diffraction losses is needed.

To capture pictures of a sample, a sharp focus of the THz beam is needed. As usual, the waist diameter depends on the wavelength and the numerical aperture (NA). Therefore a focusing THz optics with a large NA is needed.

In this paper some THz optics for photoconductive antennas (PCA) available from BATOP GmbH is compared discussing their pros and cons.

## *1. Time domain spectrometer with collimating silicon lens CL12*

### *1.1 TDS set-up*

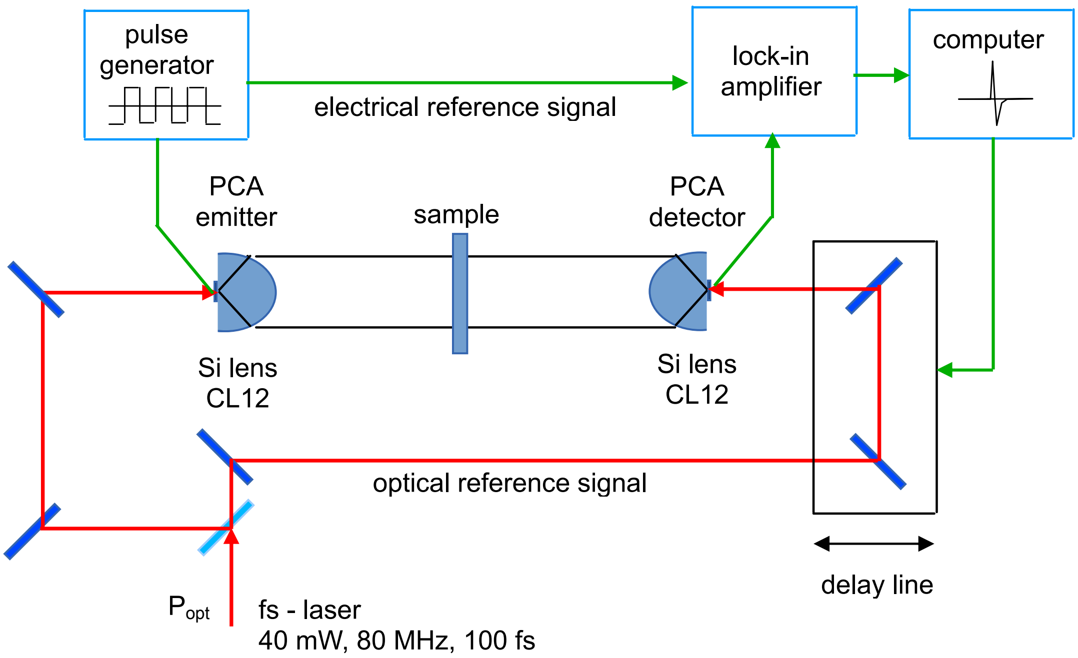


*Fig. 1 Schematic TDS set-up with collimating silicon substrate lenses*

The aspheric collimating silicon lenses CL12 with 12 mm diameter allow a very simple THz beam guiding between the emitter and detector antenna.

Because of the relative small lens diameter in comparison to the THz wavelengths the diffraction of the THz beam on the lens aperture has to be taken into account. Therefore these collimating silicon substrate lenses can be used only in case of short distances between the two PCAs up to about 10 cm.

### *1.2 Aspheric collimating silicon lens CL12*

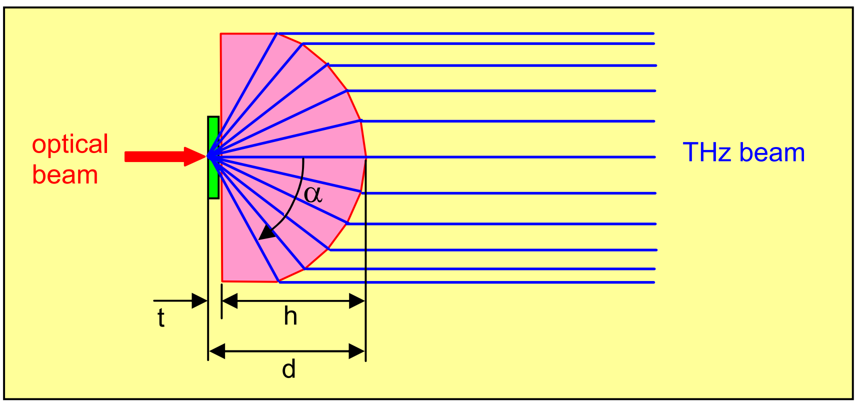


*Fig. 2 THz beam in an aspheric collimating silicon substrate lens*

| | | |
|---|---|---|
| **Aspheric lens** | diameter<br>height h<br>distance d | 12 mm<br>7.9 mm<br>8.5 mm |
| **Terahertz beam** | collimated with 12 mm diameter<br>collection angle $\alpha$ | <br>57.3° |

### *1.3 THz beam propagation*

If the THz beam is considered as a Gaussian beam, then the beam radius w(z) can be calculated along the beam propagation direction z using the formula

$$w(z) = w_0 \sqrt{1 + \left( \frac{z\lambda}{\pi (w_0)^2} \right)^2} \qquad (1)$$

with wavelength $\lambda$ and $w_0$ the beam waist, which is here 6 mm.

Using the relation f = c/$\lambda$ for the THz frequency f with c the speed of light in vacuum the beam radius w(z) is shown in figure 3 for different frequencies.

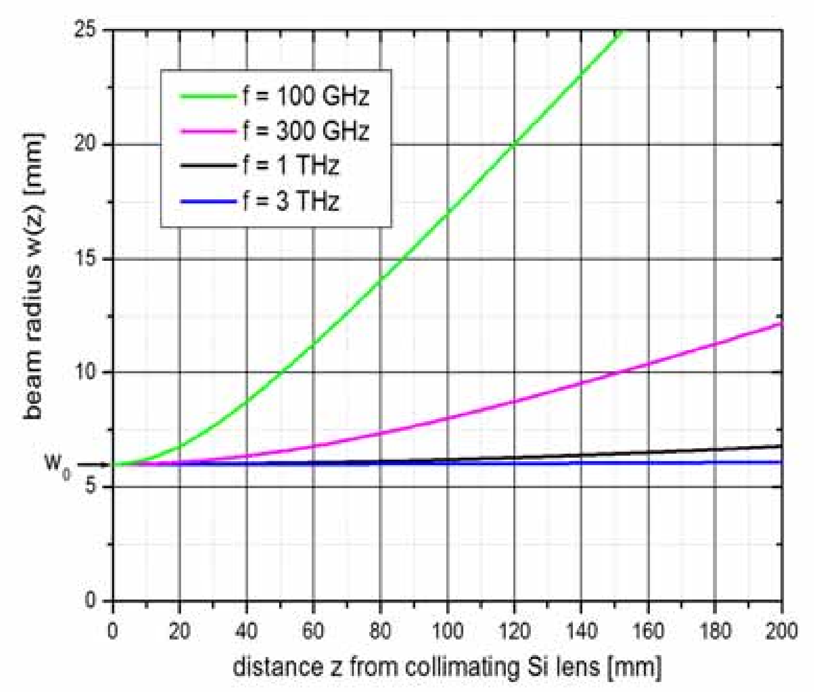


*Fig. 3 THz beam radius as a function on the distance z from the collimating silicon lens CL12 with 12 mm diameter according to equation (1).*

The beam intensity I at a point z on the beam axis can be calculated as a function of the distance z using equation (2). Here $I_0$ is the beam intensity at the position z = 0 at the silicon lens.

$$I = \frac{I_0}{1 + \left(\frac{z\lambda}{\pi w_0^2}\right)^2} \tag{2}$$

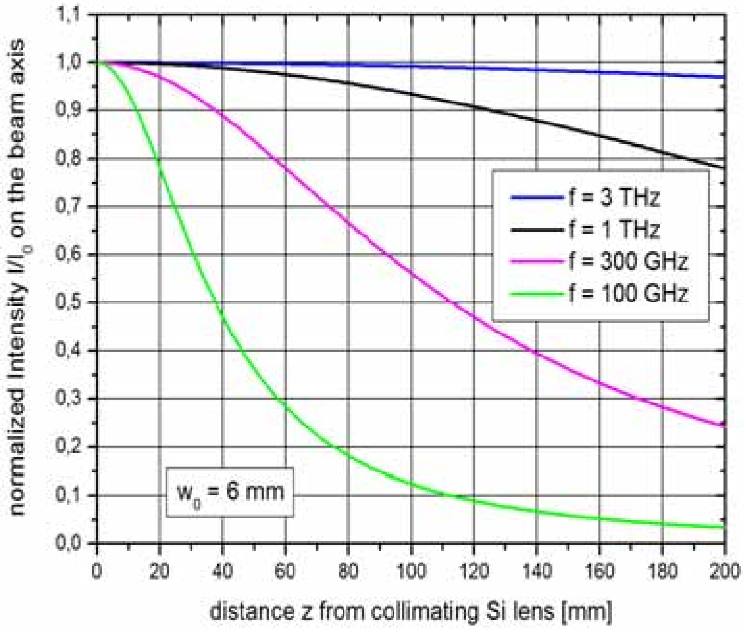


*Fig. 4 Beam intensity along the beam axis as a function of the distance z from Si lens after equation (2)*

Figure 4 above shows the drop of the normalized beam intensity $I/I_0$ according to equation (2) for different frequencies. The following statements can be deduced for using of the aspheric collimating silicon substrate lens CL12 with a lens diameter of 12 mm:

Advantages of CL12 :

- no further beam shaping elements are needed
- small footprint of the PCA head

Disadvantages:

- fast drop of the intensity after a distance of a few cm, especially at low frequencies
- the lens acts as high pass filter and suppress the low frequency part of the THz spectrum.

## 2. TDS with hyperhemispherical Si lens and collimating TPX lens CTL-D25mm

### *2.1 TDS set-up*

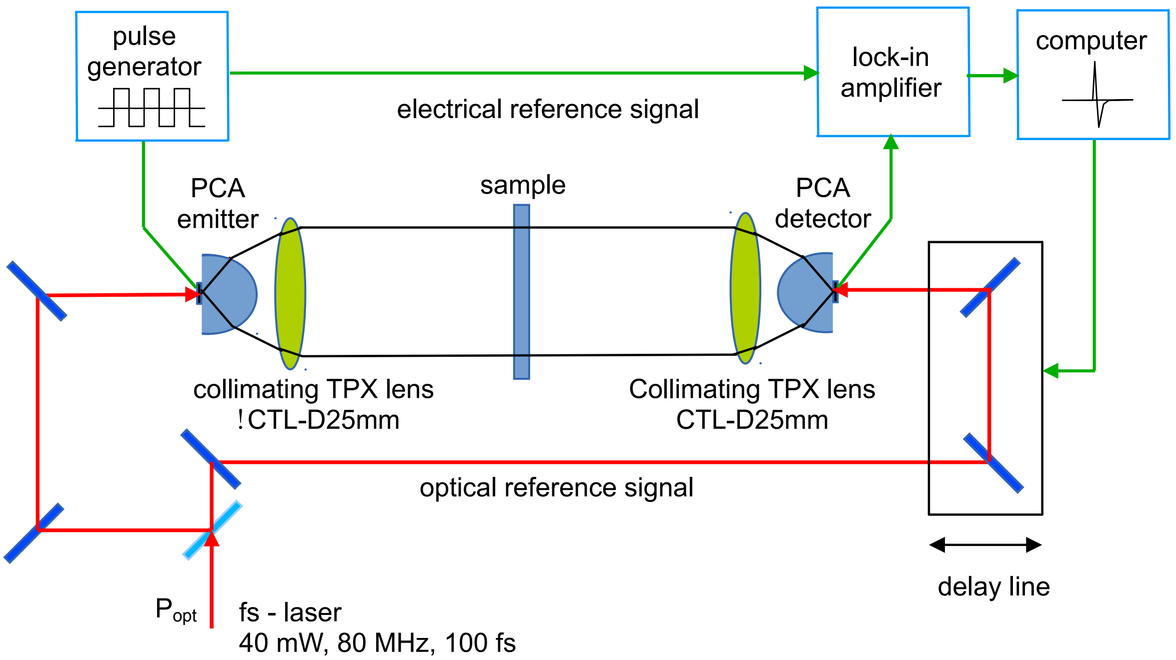


*Fig. 5 Schematic TDS set-up with hyperhemispherical silicon substrate lens and collimating TPX (Polymethylpentene) lens CTL-D25mm*

### *2.2 Hyperhemispherical Si lens + collimating TPX lens CTL-D25mm*

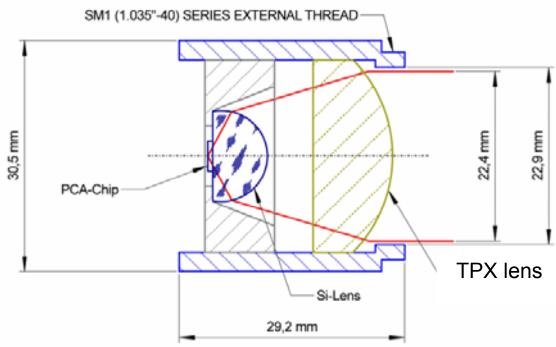


*Fig. 6 Schematic of the combination of hyperhemispherical silicon substrate lens and collimating TPX lens CTL-D25mm*

The combination of hyperhemispherical silicon substrate lens with the collimating TPX lens CTL-D25mm is shown in figure 6 above. The calculated beam intensity I at a distance z form the collimating TPA lens on the beam axis according to equation (2) is shown in figure 7.

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### *2.3 THz beam propagation*

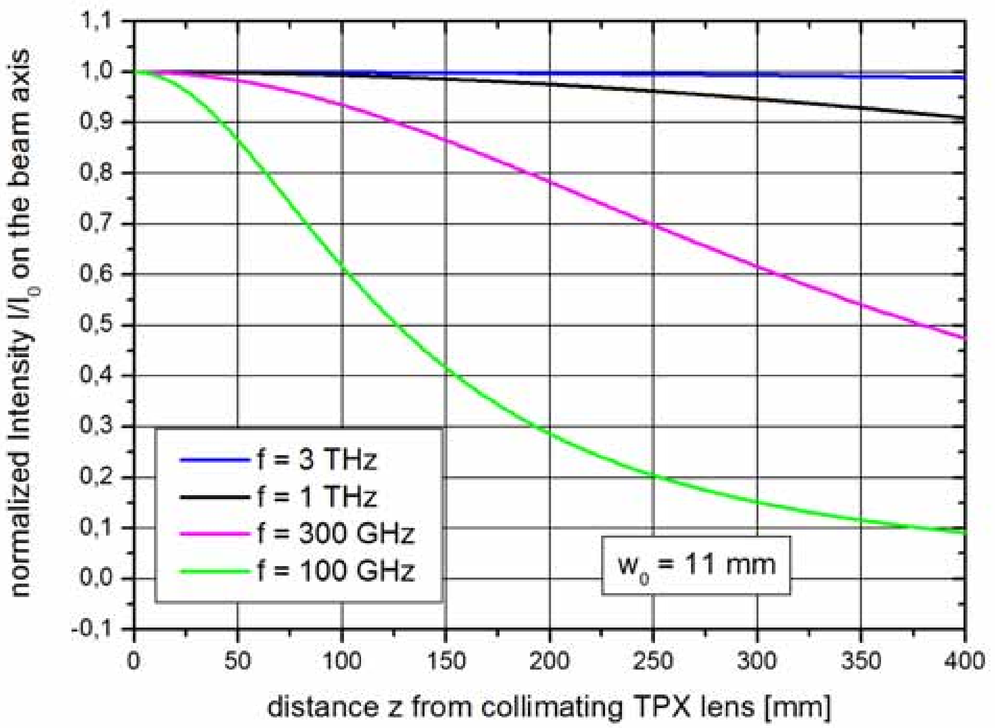


*Fig. 7 Beam intensity along the beam axis as a function of the distance z from the TPA lens according to equation (2)*

The following statements can be deduced for using the hyperhemispherical silicon substrate lens with a diameter of 12 mm in combination with the collimating TPA lens with a diameter of 22 mm:

Advantages:

- compact PCA head including the THz lenses
- decreased diffraction influence

Disadvantages:

- more optical parts must be adjusted
- longer THz paths then 10 cm results in significant drop of intensity for lower frequencies

### 3. Time domain spectrometer with focusing silicon lens FL12-f53mm

#### 3.1 TDS set-up

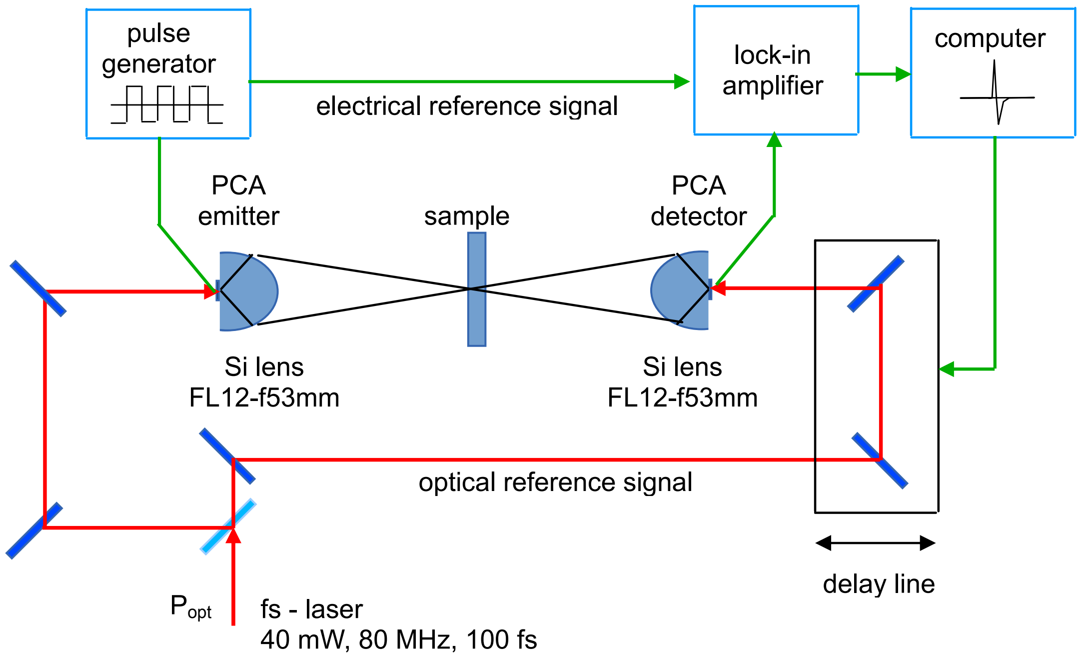


*Fig. 8 Schematic TDS set-up with focusing silicon substrate lenses FL12-f53mm*

The aspheric focusing silicon lenses FL12-f53mm with 12 mm diameter and 53 mm focus length provide a THz focus at the sample position between the emitter and detector antenna.

#### 3.2 Aspheric focusing silicon lens FL12-f53mm

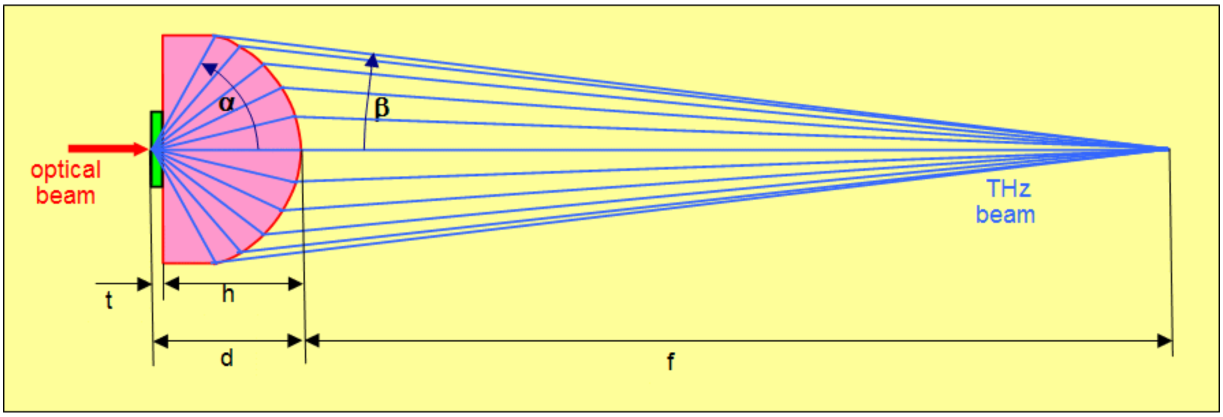


*Fig. 9 THz beam in the aspheric focusing silicon substrate lens FL12-f53mm*

| | | |
|---|---|---|
| Aspheric lens | diameter | 12 mm |
| | height h | 8 mm |
| | distance d | 8.6 mm |
| Terahertz beam | focal length $f_L$ | 53 mm |
| | collection angle $\alpha$ | 57.6° |
| | convergence angle ß | 6.8° |
| | numerical aperture NA | 0.12 |

### *3.3 THz beam waist $2w_0$*

The diameter of the beam focus $2w_0$ depends on the THz frequency f and can be estimated in case of a gaussian beam using the relation

$$2w_0 = \frac{4}{\pi}\lambda\frac{f_L}{D} = \frac{4}{\pi}\frac{c}{f}\frac{f_L}{D} \qquad (3)$$

Here $f_L$ is the focal length and D the diameter of the focusing THz lens. Besides the terahertz wavelength $\lambda$ the F* number $f_L/D$ of the lens determines the beam focus diameter $2w_0$. c is the speed of light in vacuum.

The depth of focus is two times the Rayleigh range $z_0$ and can be estimated as

$$2z_0 = \frac{2\pi(w_0)^2}{\lambda} = \frac{2\pi f(w_0)^2}{c} = \frac{8}{\pi}\frac{c}{f}\left(\frac{f_L}{D}\right)^2 \qquad (4)$$

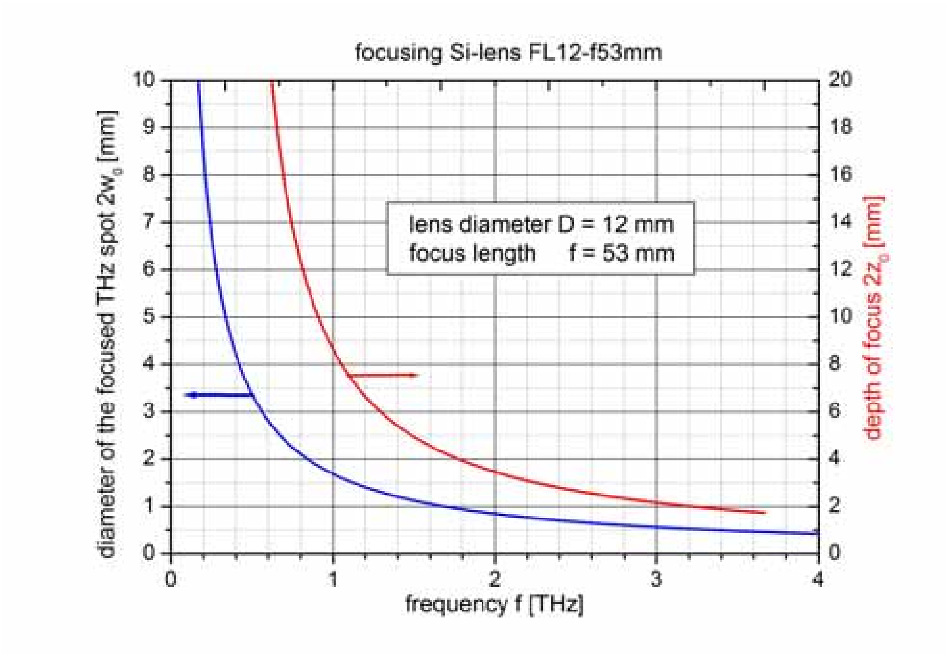


*Fig. 10 Diameter of the focused THz spot $2w_0$ (left) and depth of focus $2z_0$ (right) of the focusing silicon lens FL12-f53mm as a function of THz frequency*

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## 4. Time domain spectrometer with focusing TPX lens FTL-f30mm

### 4.1 TDS set-up

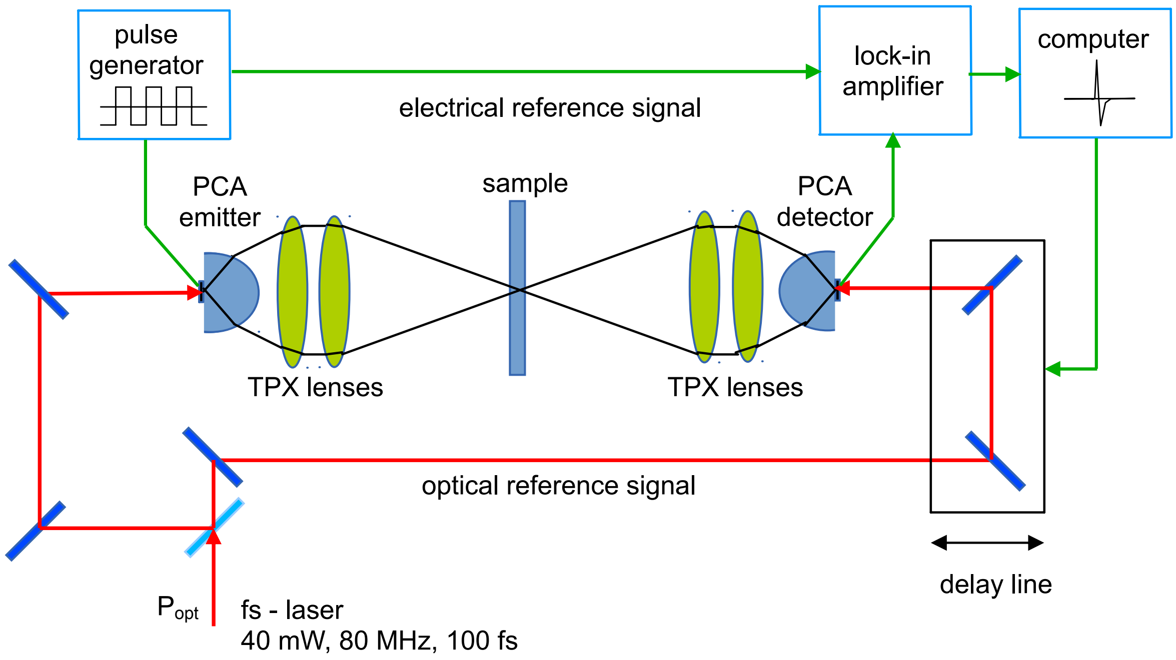


*Fig. 11 Schematic TDS set-up with hyperhemispherical silicon substrate lens and TPX lenses FTL-f30mm*

### 4.2 Focusing TPX lens FTL-f30mm

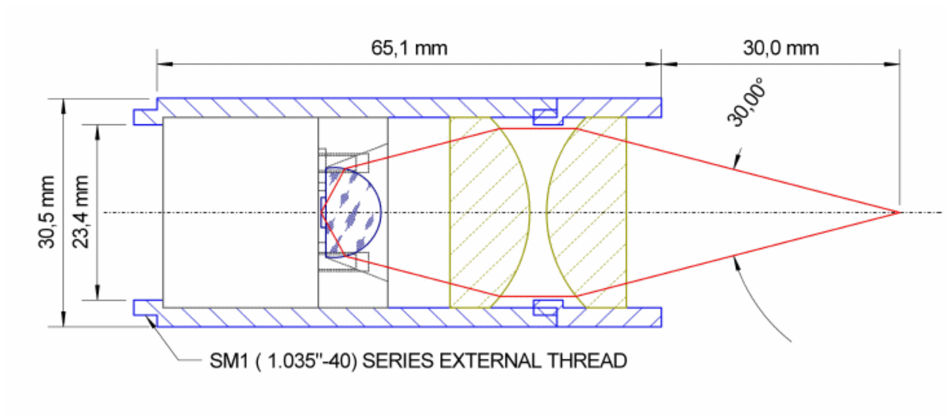


*Fig. 12 Hyperhemispherical silicon substrate lens in combination with two TPX lenses CTL-D25mm + FTL-f30mm*

### 4.3 Focused THz beam waist $2w_0$

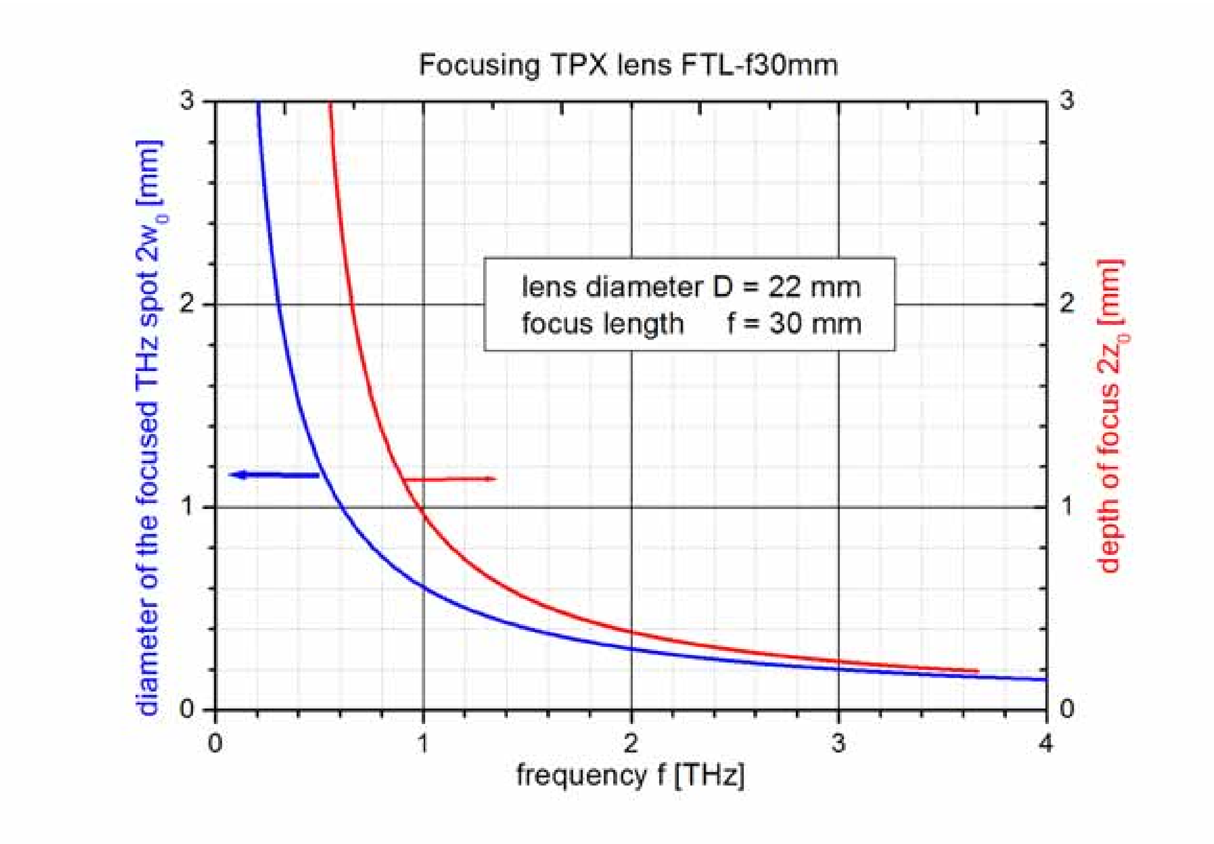


*Fig. 13 Diameter of the focused THz spot $2w_0$ (left) and depth of focus $2z_0$ (right) of the focusing TPX lens FTL-f30mm according to equation (3)*

Advantages:

- compact PCA head including the THz lenses
- high F* number of 0.63 resulting in a small THz focus

Disadvantage:

- more optical parts have to be adjusted

## 5. Conclusions

- For larger THz beam distances a larger beam diameter (using larger lens diameters) is needed
- To get a small THz beam focus a high F* number of the focusing lens is important
- Because of the broad THz spectrum the diffraction limited beam diameter depends strong on the frequency