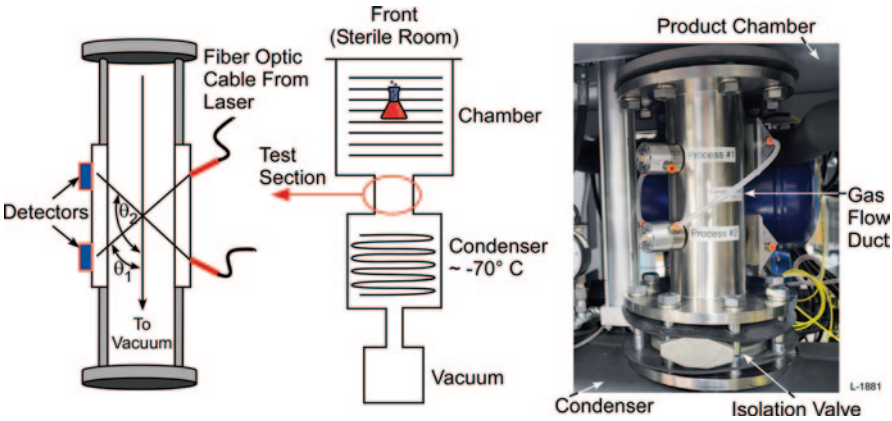

Fig. 14 Schematic diagram of the Doppler-shift absorption spectroscopy velocity measurement concept and a spool outfitted with two optical detection paths installed in a Lyostar 3® lyophilzer

line within the v_3+v_2 vibrational band), water vapor absorption feature is chosen due to its strong line strength, its weak temperature dependence (~2.7% per 10 K gas temperature change under conditions of interest during lyophilization [51]) and to leverage the existence of robust telecommunications grade, fiber-coupled diode lasers.

The measurement of the gas flow velocity within the duct connecting the lyophilizer product drying chamber and the condenser is enabled by orienting the laser beam vectors (**k**) crossing the duct at an angle ($\boldsymbol{\theta}_1$ and $\boldsymbol{\theta}_2$) with respect to the gas flow vector (**u**). This measurement architecture results in a Doppler shift of the absorption lineshape to higher or lower frequencies depending upon the orientation of the laser light propagation with respect to the gas flow. Figure 14 shows a schematic diagram of a two line-of-sight measurement configuration across the flow duct and a photograph of the optical setup mounted within a Lyostar 3 laboratory-scale freeze-dryer. Using two line-of-sight measurements across the duct results in two simultaneously recorded lineshapes shifted to higher and lower frequencies and enables the determination of the gas flow velocity, u, using Eq. 10 [52]:

$$u = \frac{c \cdot \Delta v}{v_o \cdot (\cos\theta_1 - \cos\theta_2)} \tag{10}$$

where c is the speed of light (3×10^{10} cm/s), Δv is the peak absorption shift between the two absorption lineshapes in cm^{-1}, v_o (7181 cm^{-1}) is the absorption peak frequency at zero flow velocity, and θ_1 and θ_2 are the angles formed between the laser propagation vectors across the flow and the gas flow vector. The frequency shift, Δv, is determined by the shift in data points between the two absorption profiles and converted to absolute frequency using the calibrated diode laser frequency scan rate (cm^{-1}/point).