Tapered Hollow-Core Fibers Providing Single-mode Output in the 3.5 µm –7.8 µm Spectral Range

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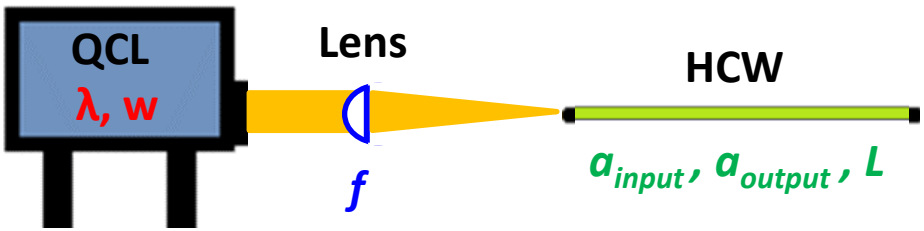
Outline

- Introduction
- Theoretical model
- Experimental results
- Conclusions

Hollow-Core Waveguides

$$a(z) = \frac{a_{output} - a_{input}}{L} z + a_{input}$$

Collimated Laser Beam-HCW Optical Coupling



- **Diffraction-limited collimated Gaussian beam**
- **Focal length:** $$f = \frac{R}{1+\left(\frac{\lambda R}{\pi w^2}\right)^2}$$
- **Waist radius at the focal plane:** $$w_0 = \frac{w}{\sqrt{1+\left(\frac{\pi w^2}{\lambda R}\right)^2}}$$
- **Beam intensity distribution:** $$G(r) = G_0 e^{-\frac{r^2}{w_0^2}}$$

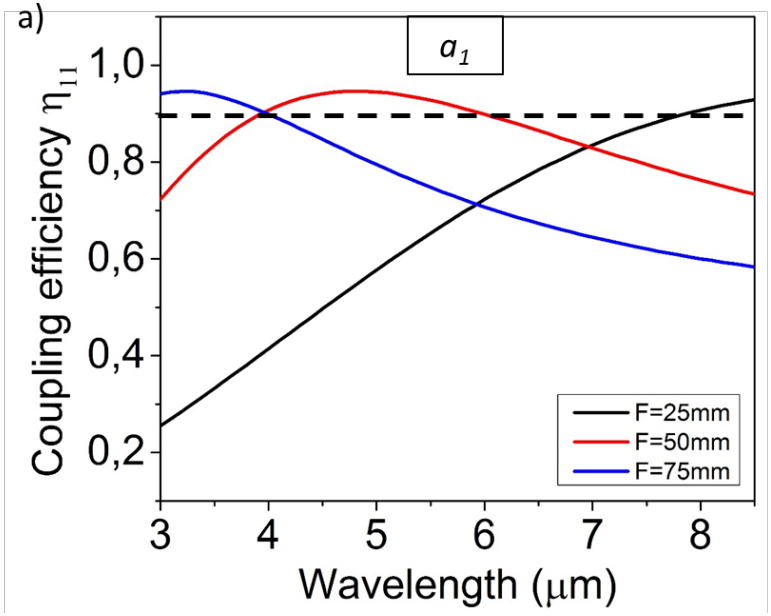
Coupling efficiency

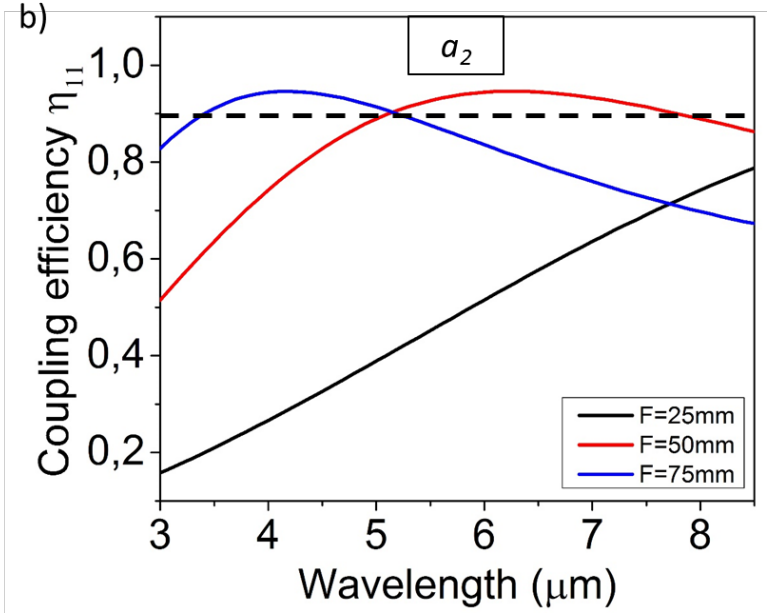
- **HCW hybrid modes: zero-order Bessel functions:** $J\left(u_{1m}\frac{r}{a_{input}}\right)$

- **Power coupling efficiency:**

$$\eta_{1m} = \frac{\left|\int_0^{a_{input}} G(r) J\left(u_{1m}\frac{r}{a_{input}}\right) r dr\right|^2}{\int_0^{a_{input}} G(r)\, r dr \int_0^{a_{input}} J\left(u_{1m}\frac{r}{a_{input}}\right) r dr}$$

Depends only on a_{input}





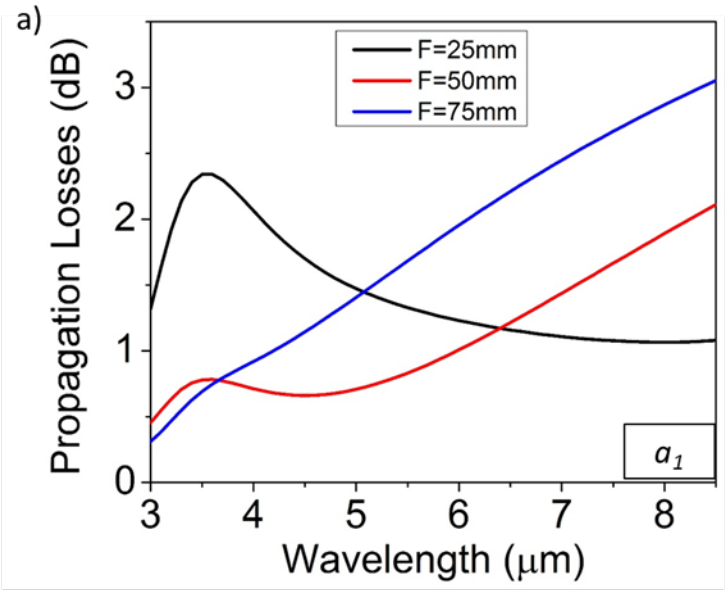
Propagation Losses

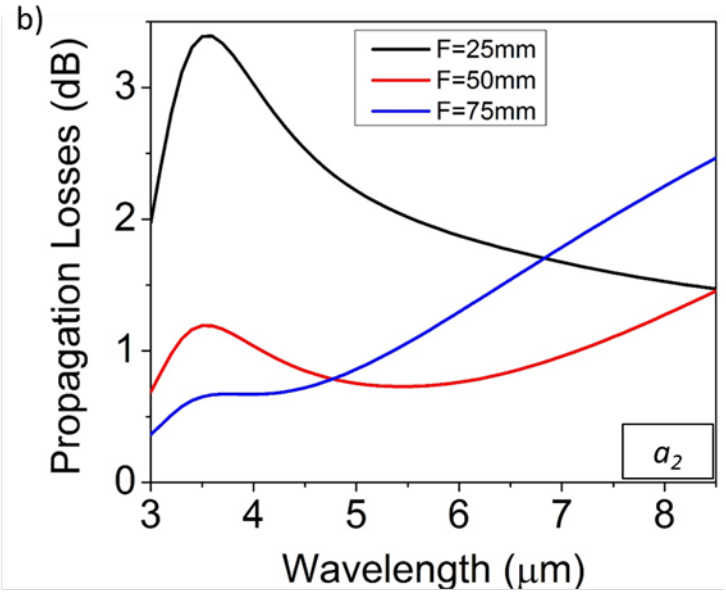
- **Attenuation coefficient:** $$\alpha_{1m} = \left(\frac{u_{1m}}{2\pi}\right)^2 \frac{\lambda^2}{a(z)^3} \frac{n}{n^2+k^2} \frac{1}{2}\left(1+\frac{n_d^2}{\sqrt{n_d^2-1}}\right)^2 = K\frac{u_{1m}^2\lambda^2}{a(z)^3}$$

- **Theoretical Losses:** $$L_p(dB) = -10Log_{10}\left(\sum_m \eta_{1m}\exp\left(-2\int_0^L \alpha_{1m}(z)dz\right)\right)$$

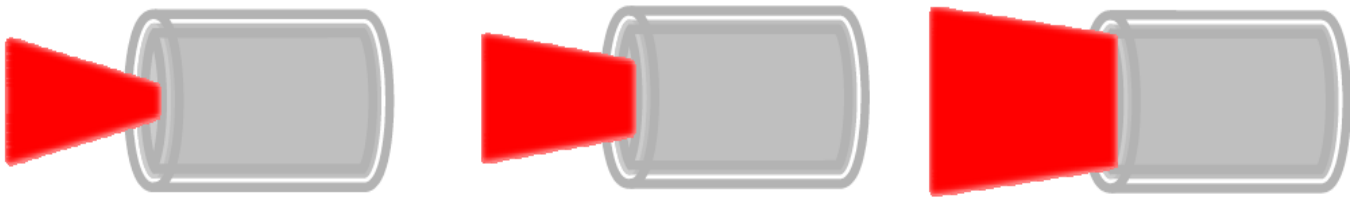
$$-10Log_{10}\left(\sum_m \eta_{1m}\exp\left(-2Ku_{1m}^2\lambda^2 L\frac{a_{input}+a_{output}}{2a_{input}a_{output}}\right)\right)$$

Depends both on *a_{input}* and *a_{output}*





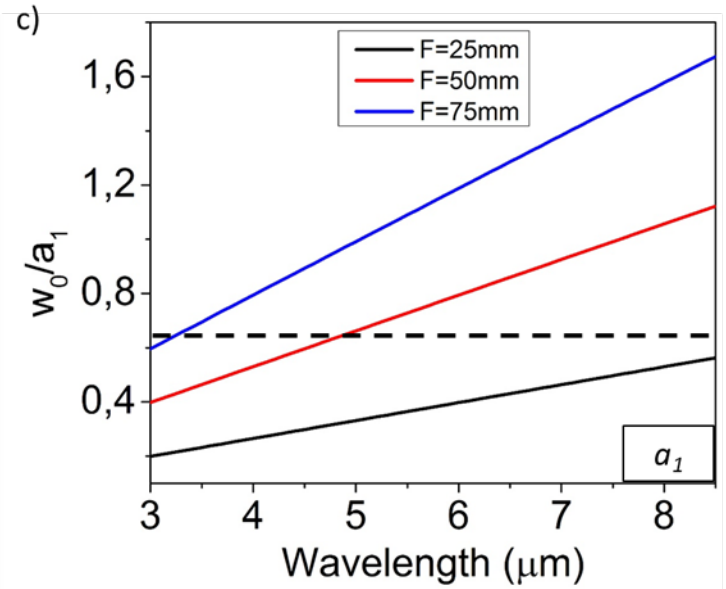
w_0/a_{input} Parameter

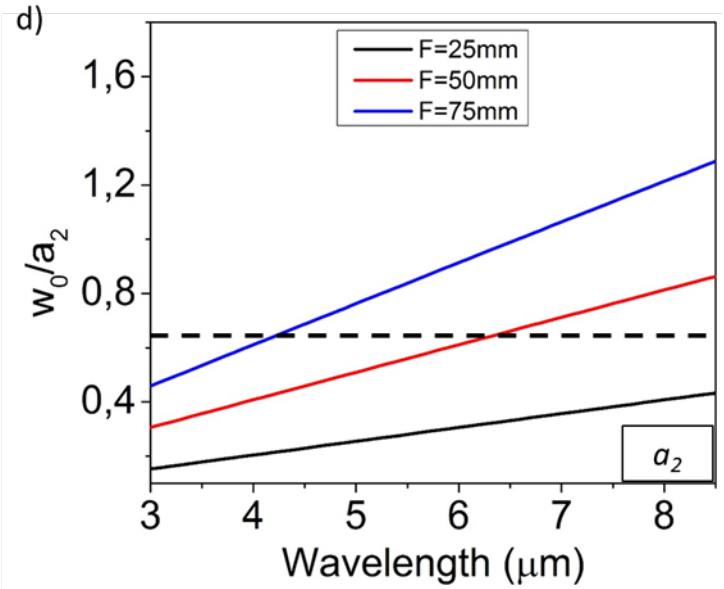


Under-fill:
Excite higher order modes

$w_0/a=0.64$
Optimal coupling

Over-fill:
Beam is clipped

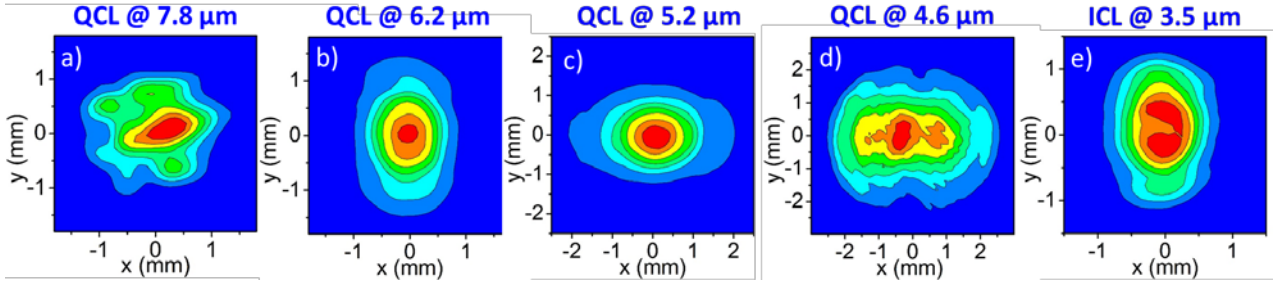


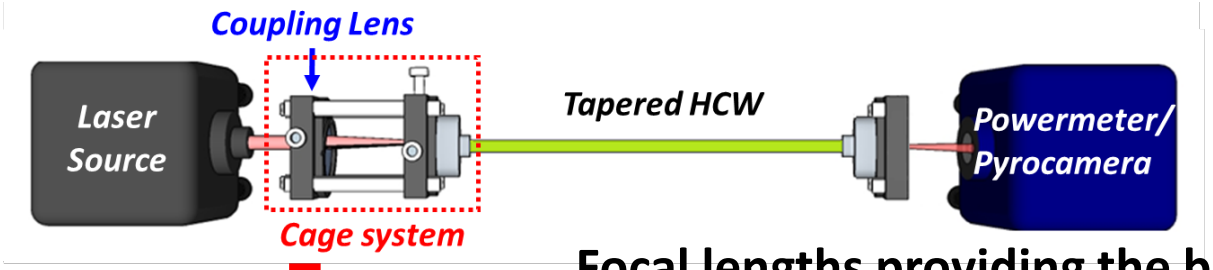


Experimental Setup

Optical coupling with five lasers in the mid-IR spectral range

Beam profiles acquired at the lasers exit





Focal lengths providing the best coupling conditions

		7.8 µm QCL	6.2 µm QCL	5.2 µm QCL	4.6 µm QCL	3.5 µm ICL
a_1	f	25 mm	50 mm	50 mm	75 mm	75 mm
	η_{11}	89.6%	88.6%	94.0%	83.6%	93.8%
	w_0/a_1	0.52	0.82	0.69	0.91	0.70
a_2	f	25 mm	50 mm	75 mm	75 mm	75 mm
	η_{11}	72.2%	94.6%	89.9%	93.6%	91.1%
	w_0/a_2	0.40	0.63	0.80	0.70	0.54

Beam Profiles at Tapered-HCW Exit

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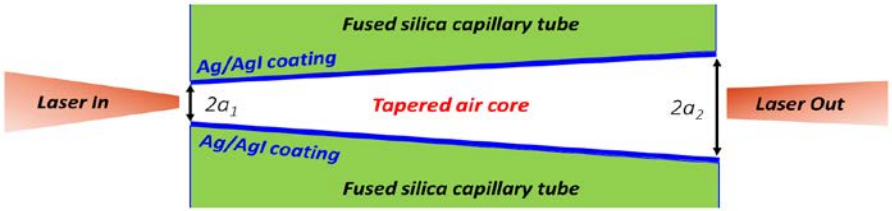
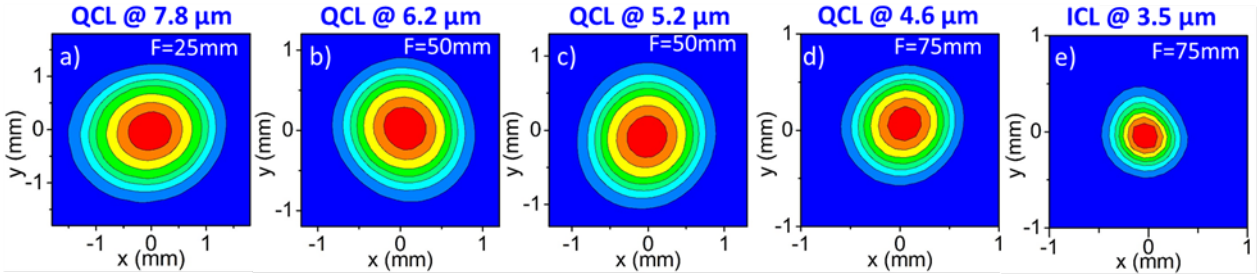
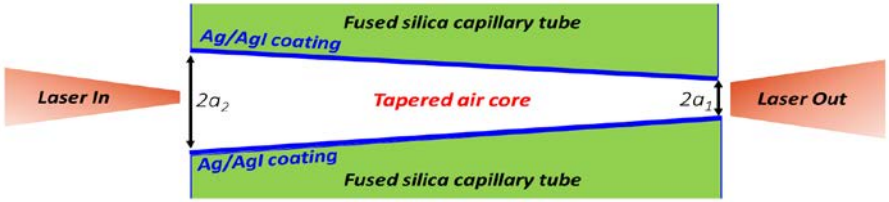
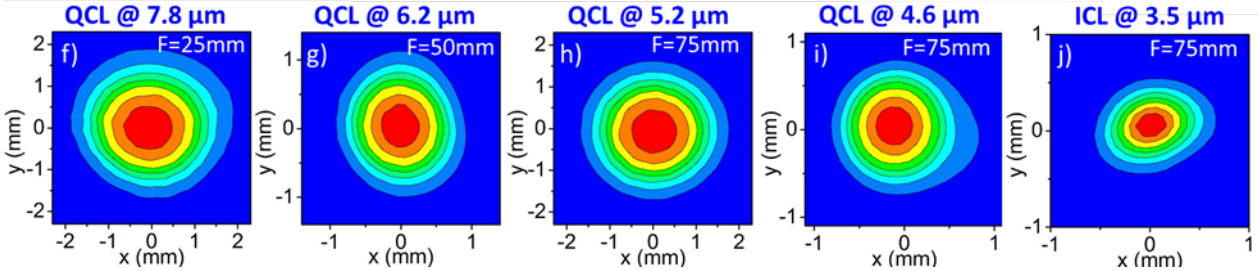
- **Input bore radius: a_1**





- **Input bore radius: a_2**





Single mode output when a_1 or a_2 as input bore radius

Influence of w_0/a Parameter on the Beam Quality

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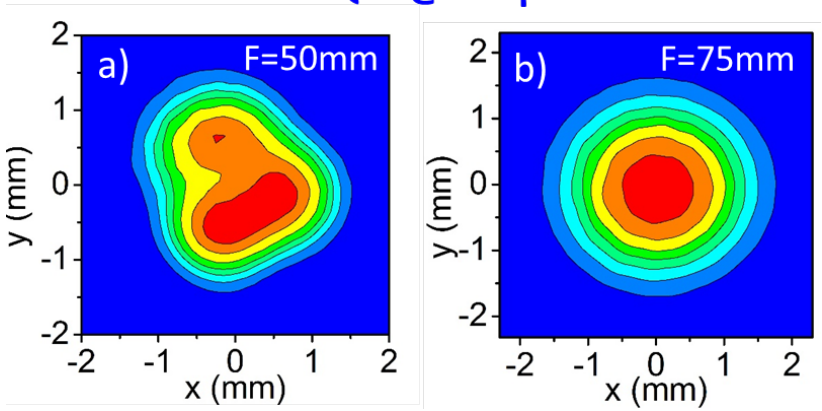
Example of 5.2 µm QCL coupled into input bore radius a_2

- F= 50 mm and F=75 mm allowing the same coupling efficiency of the laser power with the J_{11} mode

f	50 mm	75 mm
η_{11}	90.1%	90 %
Propagation Losses	74 dB	93 dB
w_0/a_1	0.53	0.80

QCL @ 5.2 µm

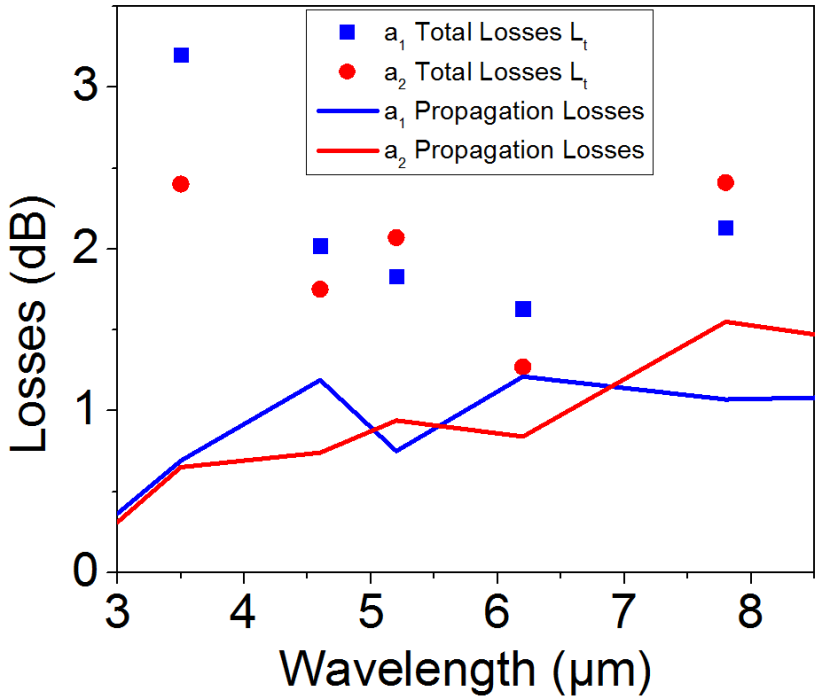


Although 90% coupling efficiencies, a w_0/a_2 value substantially lower than 0.64 does not guarantee a single-mode output

Total Losses vs Theoretical Losses

- **Experimental Total Losses**

$$L_t(dB) = -10Log_{10}\frac{P_{out}}{P_{in}}$$



For each laser, lower losses when using the input side a_i giving the larger η_{11}

Discrepancy ascribed to

- **low spatial quality of the laser beams**
- **at 3.5 µm: scattering losses $\propto 1/\lambda^2$, caused by HCW inner surface roughness**

Conclusions

- **Study on the influence of *f*, λ and *a* on Tapered-HCW performance**
- **Theoretical model predicting the best operating conditions for single-mode output and low optical losses**
- **Experimental validation of the model in the 3.5-7.8 µm spectral range**
- **Selection of the coupling inner bore a_i allowing single-mode output with the lowest losses**

	7.8 µm QCL	6.2 µm QCL	5.2 µm QCL	4.6 µm QCL	3.5 µm ICL
f	25 mm	50 mm	50 mm	75 mm	75 mm
2w	1.9 mm	2.3 mm	2.8 mm	3.5 mm	1.9 mm
A	a_1	a_2	a_1	a_2	a_2
η_{11}	89.6%	94.6%	94.0%	93.6%	91.1%
w_0/a	0.52	0.63	0.69	0.70	0.54
L_t (dB)					
Beam Profile