Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Terahertz Wireless Communications: A Photonics Approach
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Abstract: To accommodate the rapid increase in global wireless traffic, which will reach to 49 exabytes per month by 2021, wireless networks operating beyond 95 GHz will very likely be required. The operation and characteristics of such networks are quite different from those of conventional wireless systems, or even of 5G systems which will employ millimeter-wave links at lower frequencies. The distinctions arise from the much shorter wavelength, which implies both a significantly higher directionality and a very different propagation and diffraction characteristic. This offers both challenges and opportunities for future networks operating at these frequencies. In this presentation, we discuss several new measurements to characterize aspects of these high-frequency channels, including non-line-of-sight links. A first study of the implications of high directionality on eavesdropping and physical-layer security will also be described.

Purpose: Information on terahertz technology

Terahertz wireless communications: A photonics approach

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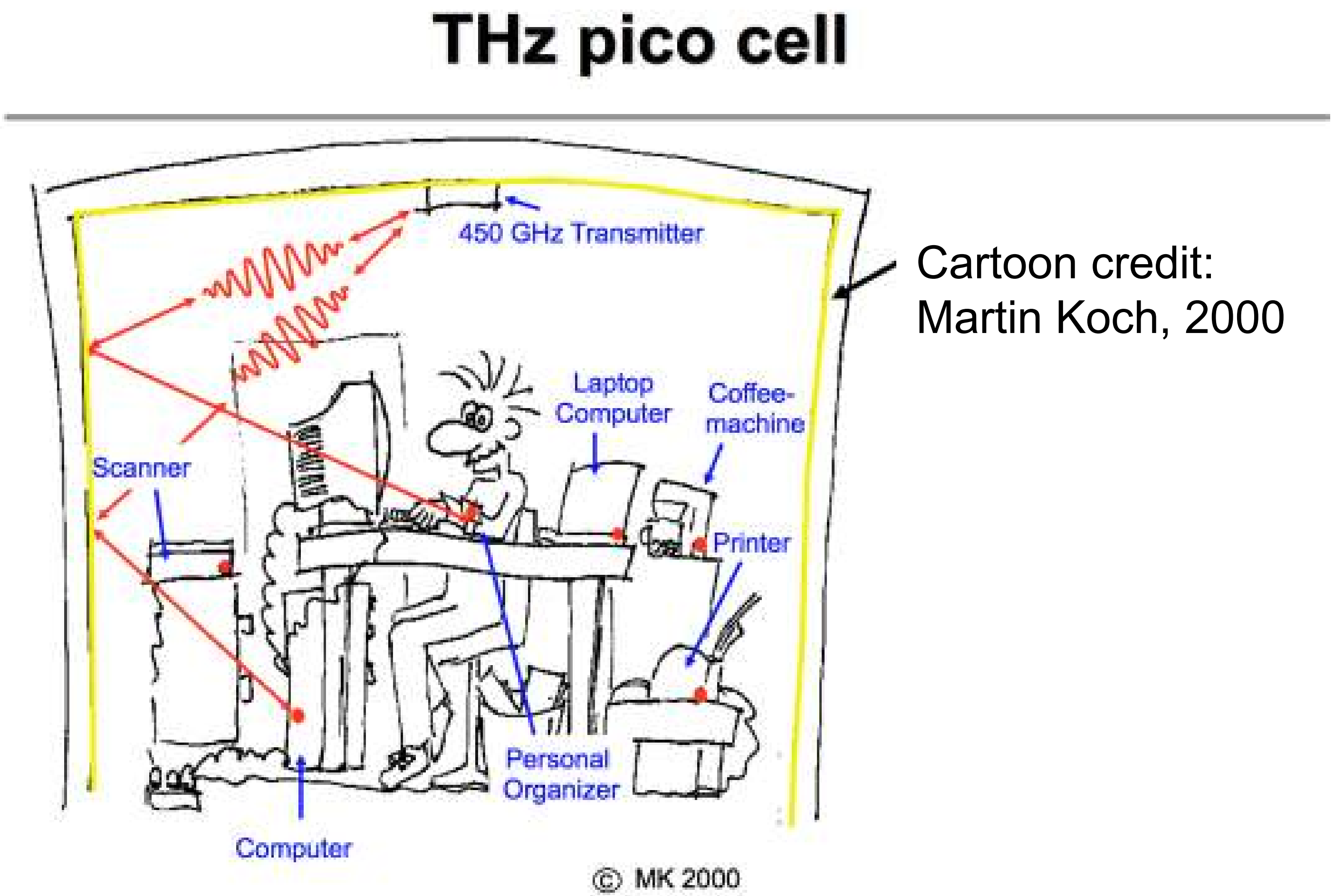
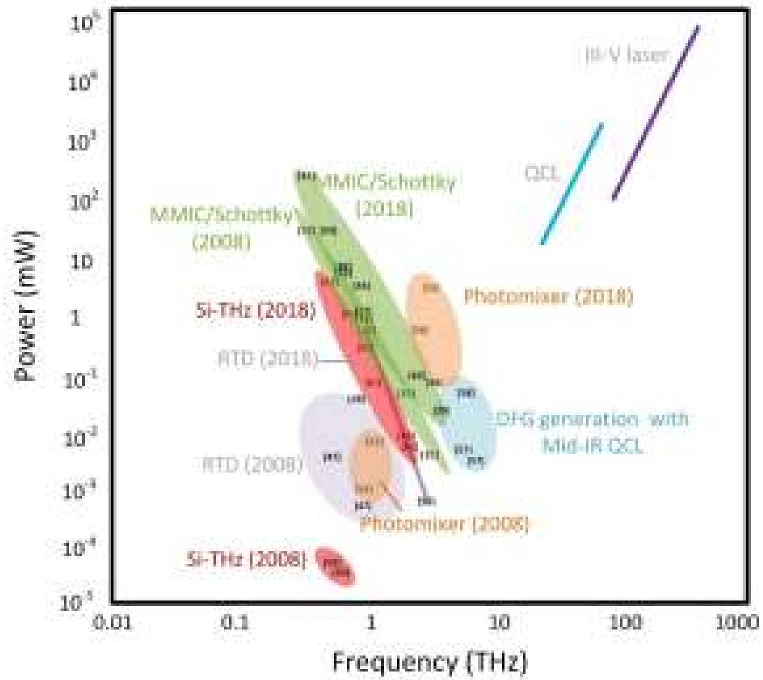
Terahertz wireless pico-cells: a vision

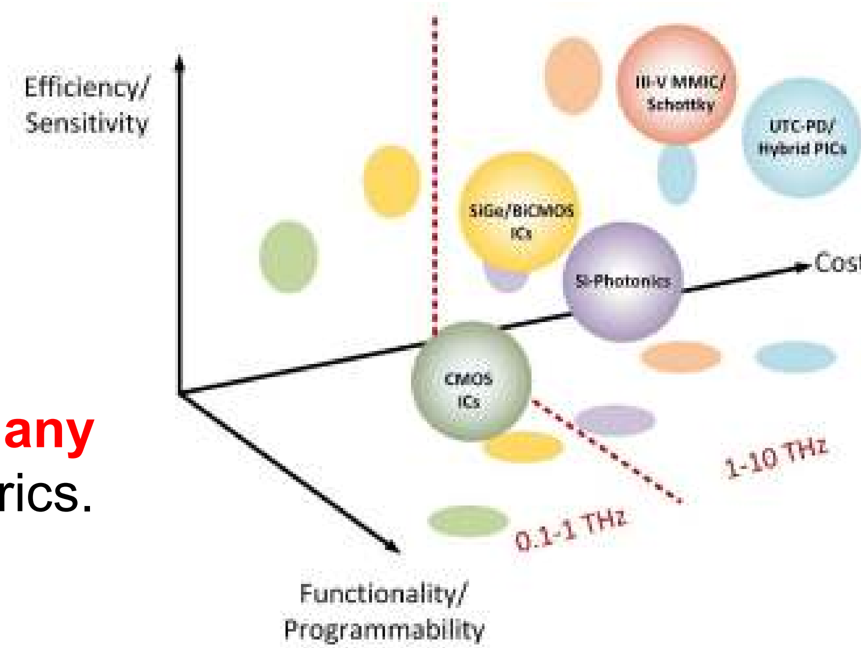


Cartoon credit:
Martin Koch, 2000

THz systems: an ongoing merger of electronics and photonics



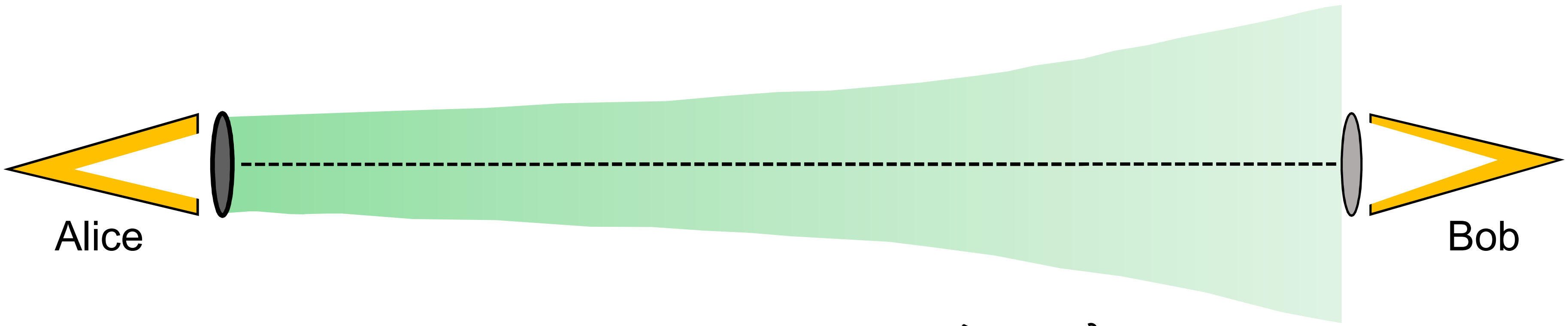
Lots of progress in recent years in some key metrics…



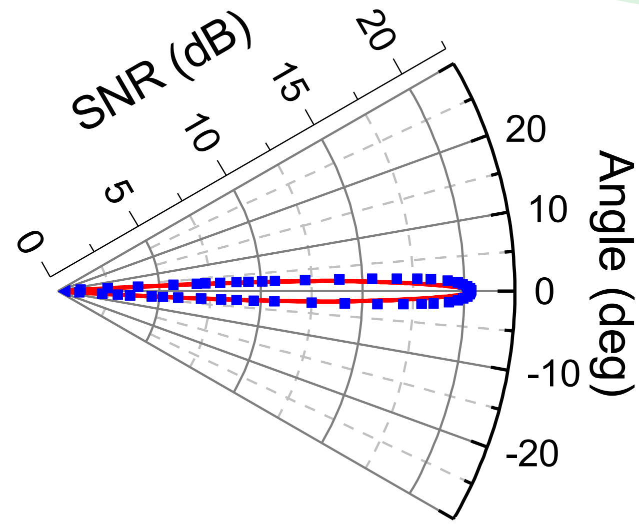
…but there are **many** important metrics.

A recent review:
K. Sengupta, T. Nagatsuma, & D. Mittleman, *Nature Electronics*, 1, 622 (2018).

THz links are highly directional



Signals which propagate as beams, not broadcasts, can often conveniently be envisioned through the lens of optics.

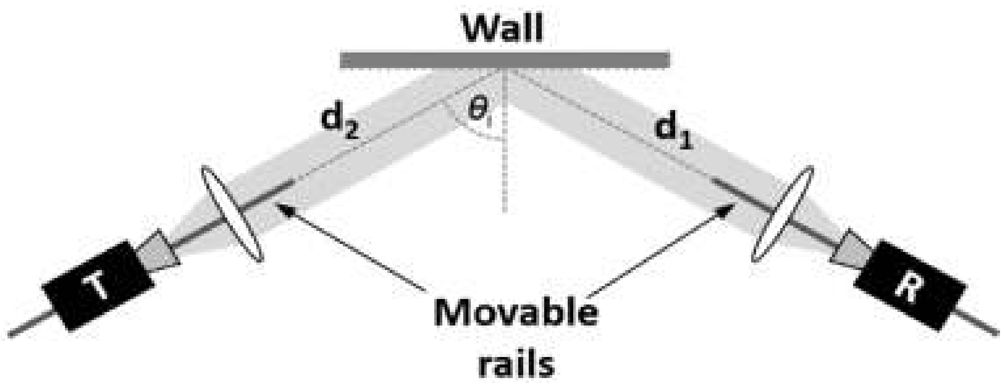


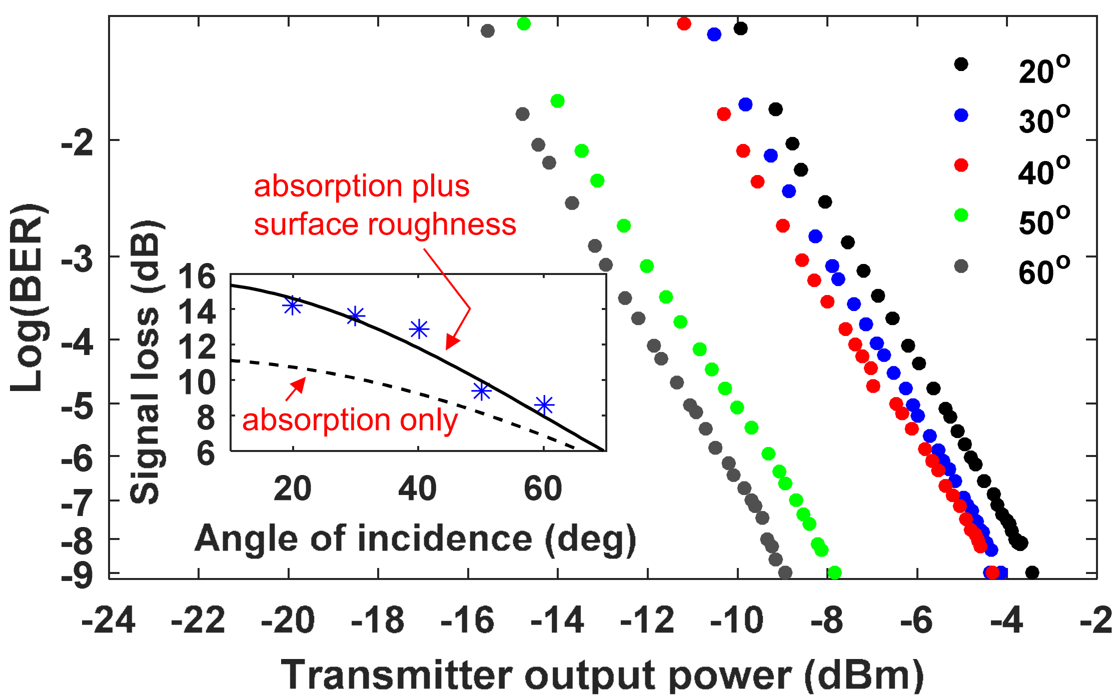
Brown University test bed:

Frequency	100 GHz	200 GHz	400 GHz
Directivity	28 dBi	34 dBi	42 dBi
Angular width	7.8º	4.0º	1.6º

Reflections off a wall

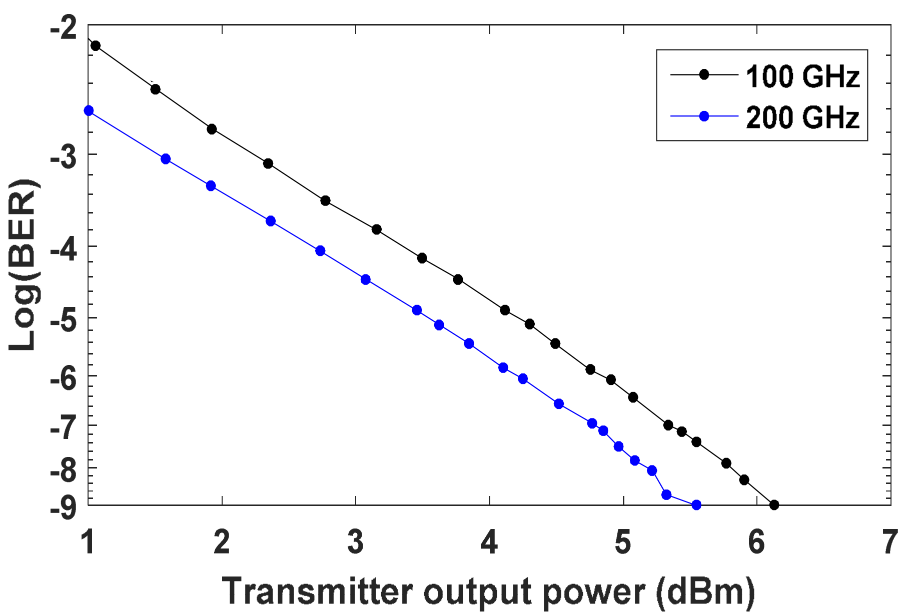
Model accounts for
- absorption
- surface roughness

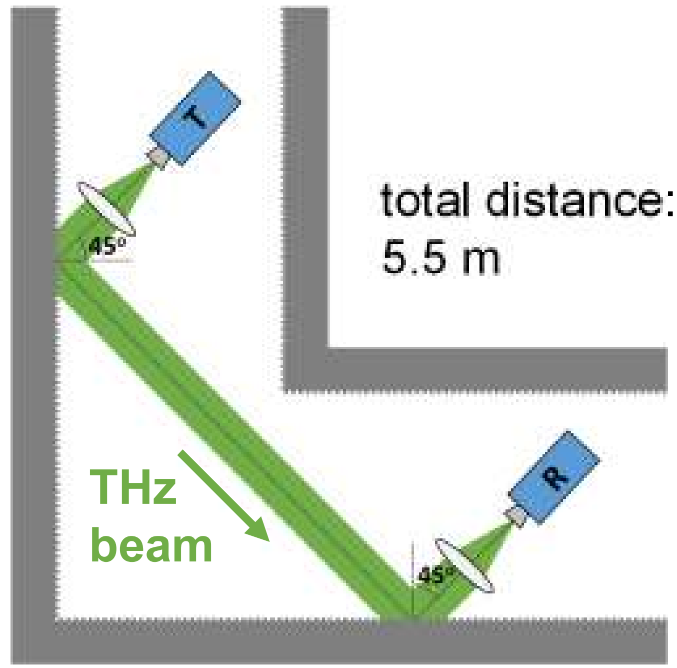




J. Ma, et al., *APL Photonics*, **3**, 051601 (2018)

A link with no direct line-of-sight path

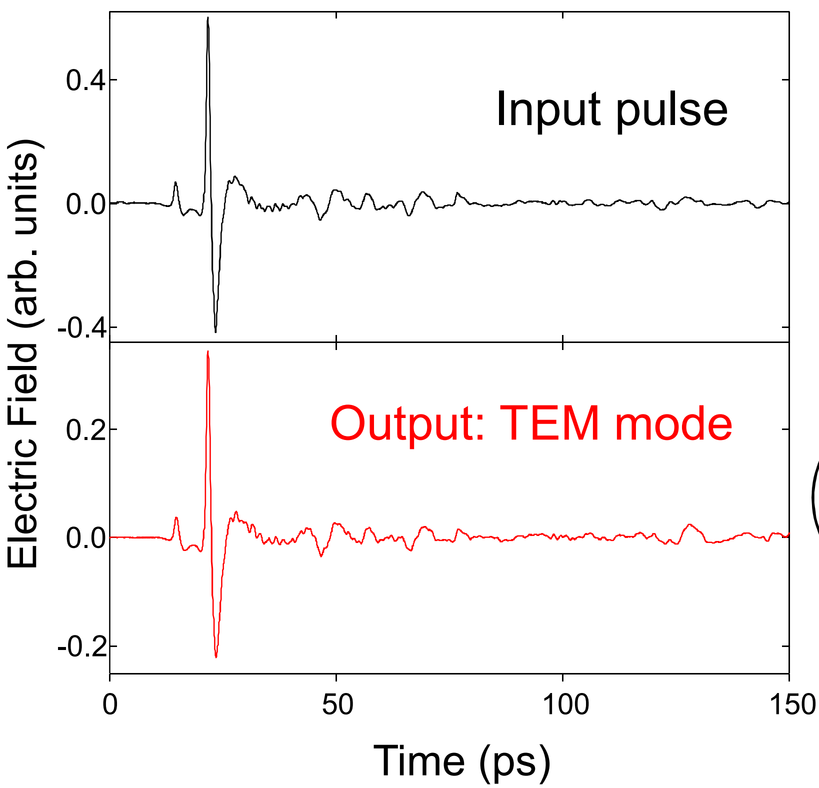


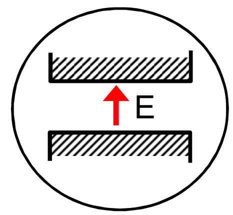


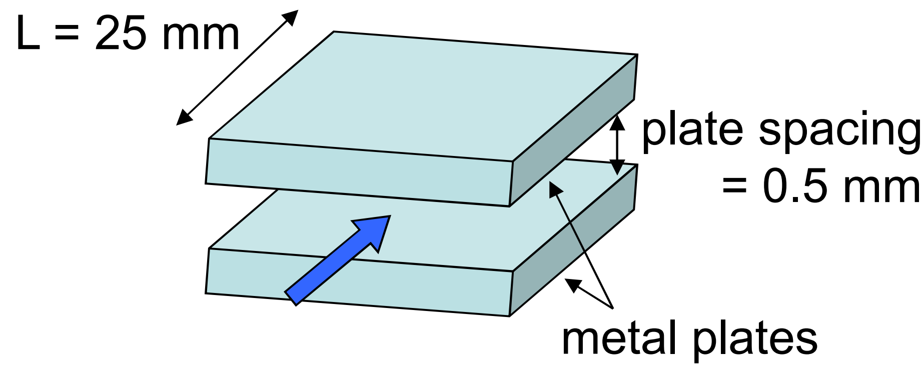
Specular non-line-of-sight links are surprisingly robust in indoor environments.

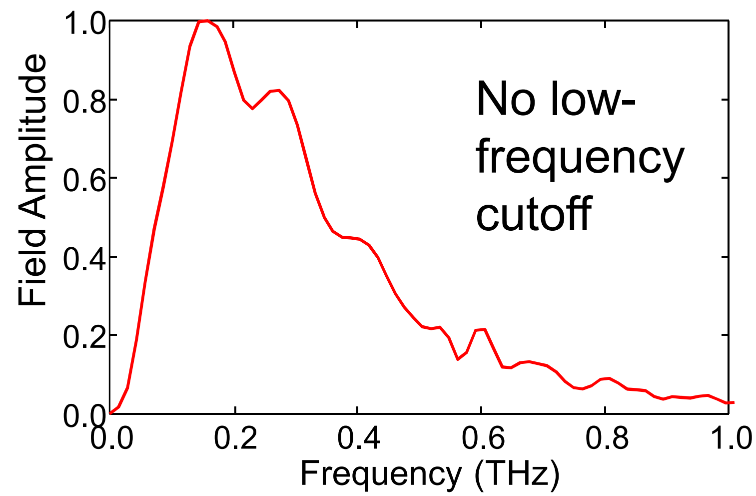
J. Ma, et al., *APL Photonics*, **3**, 051601 (2018)

Metal parallel-plate waveguides: a platform for terahertz devices



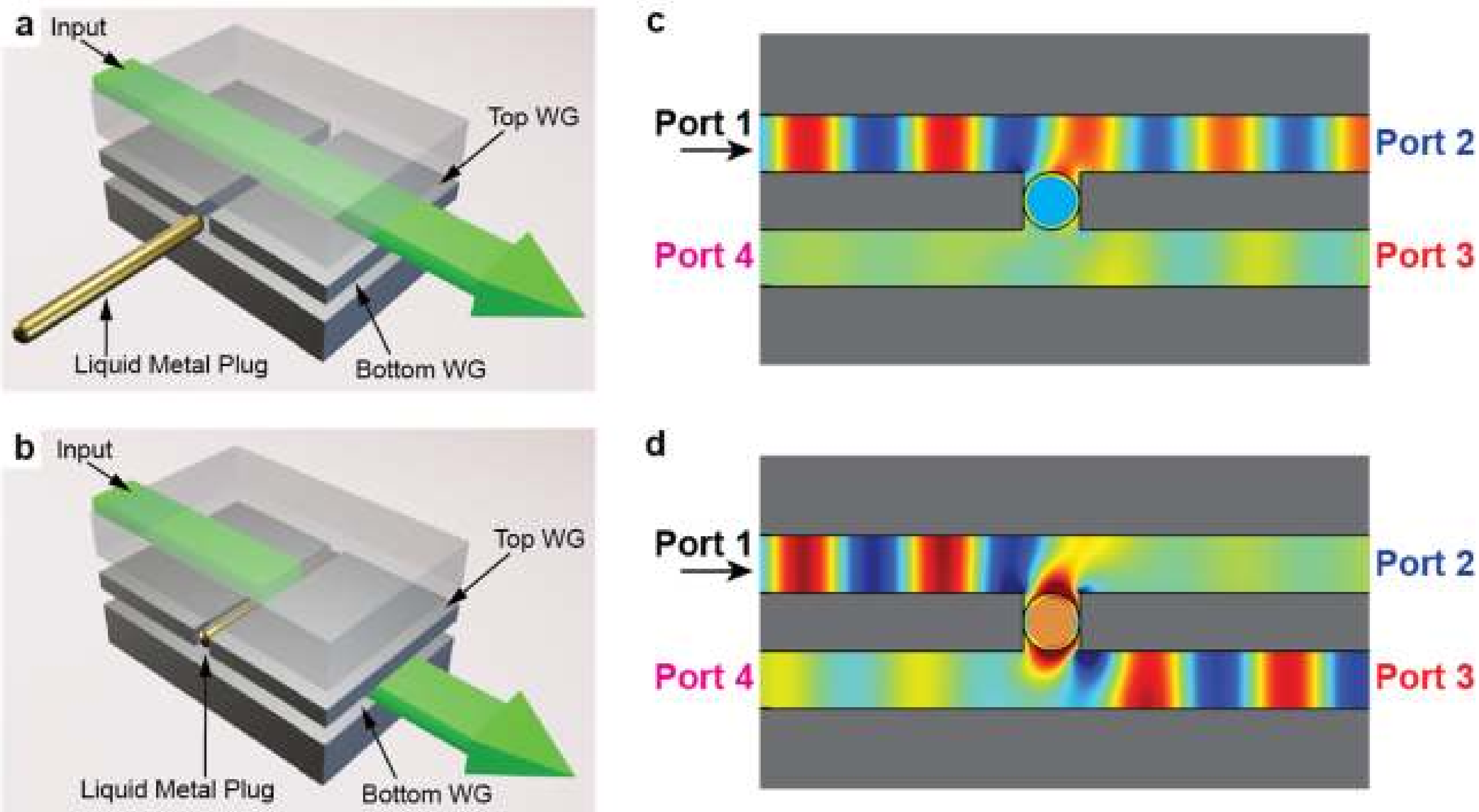






R. Mendis and D. Mittleman, *Opt. Express*, **17**, 14839 (2009).

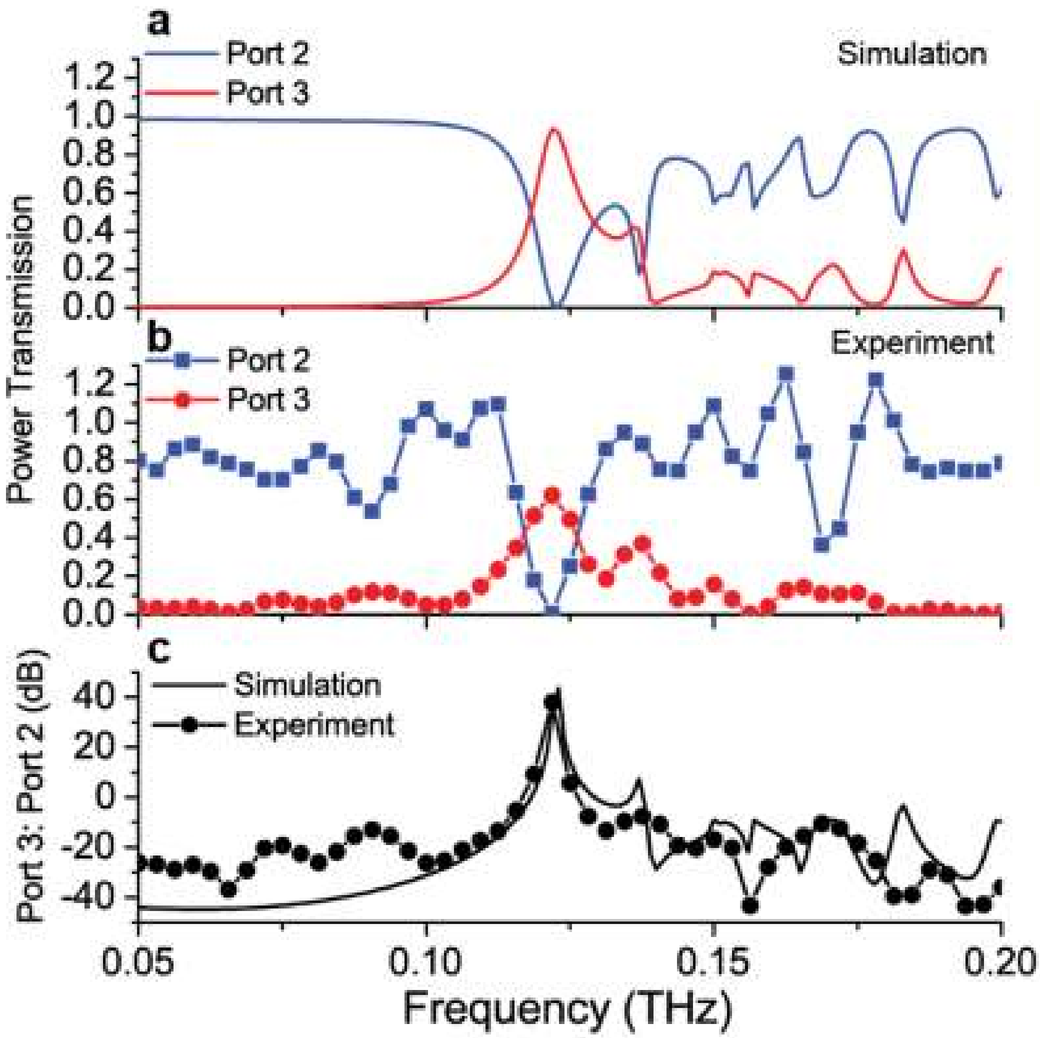
Coupling two waveguides together

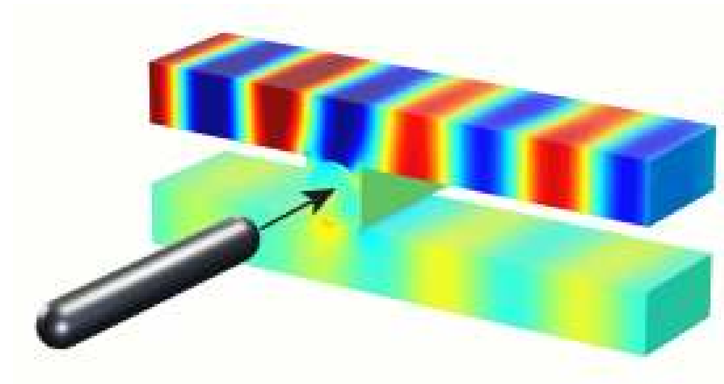


Key component: electrically actuated liquid metal plug

Collaboration with: M. D. Dickey, North Carolina State University

Electrically actuated filter at 120 GHz



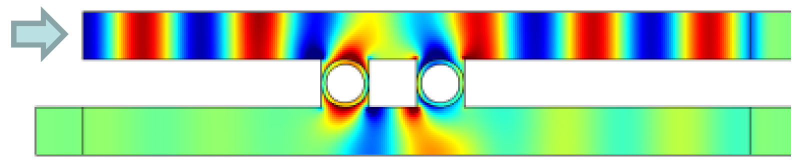


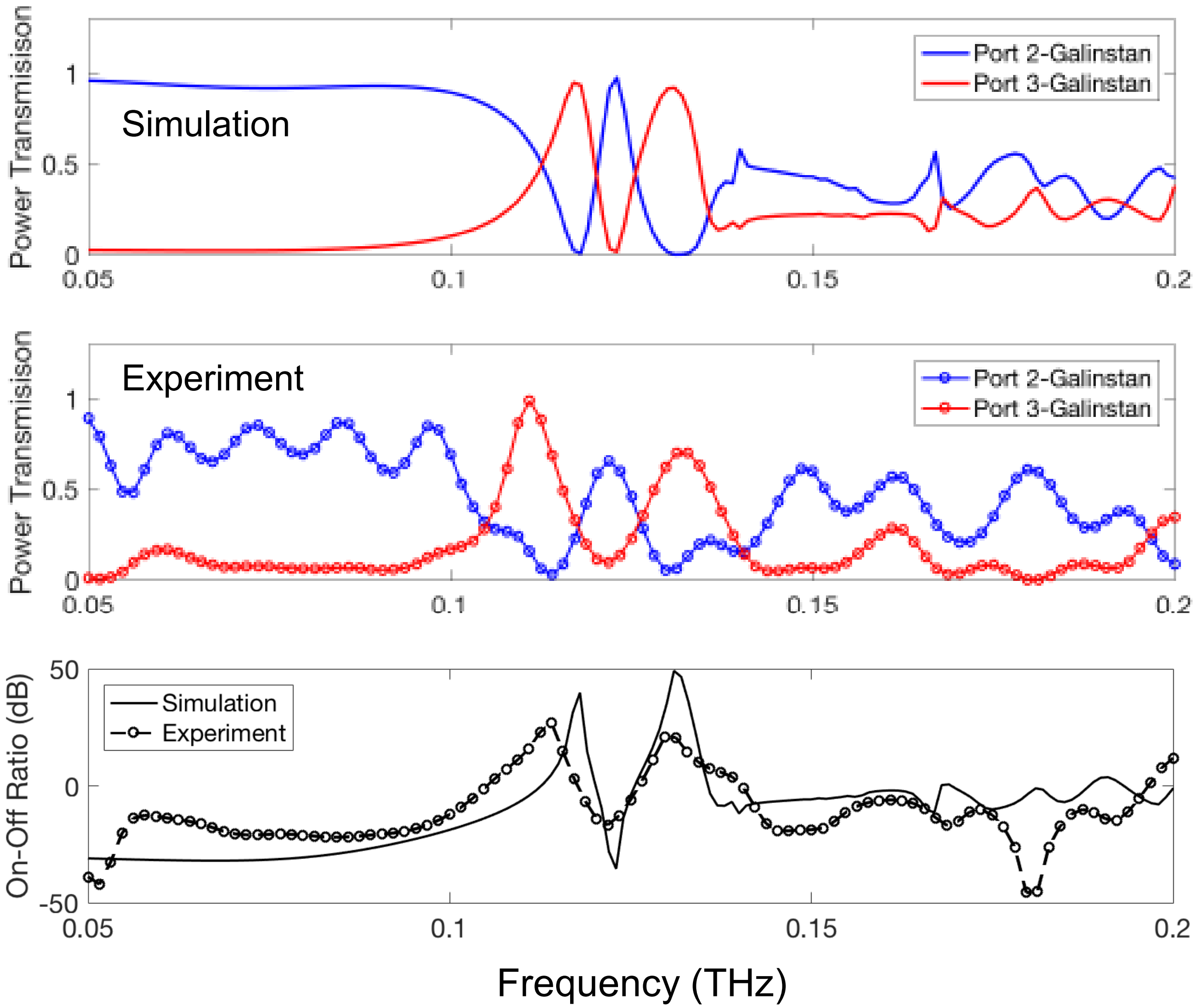
Resonant coupling between two adjacent waveguides.

Frequency determined by geometry of coupling region – a classic problem in optics!

K. Reichel, et al. *Nature Commun.* **9**, 4202 (2018)

Multi-channel add-drop filter for frequency multiplexing





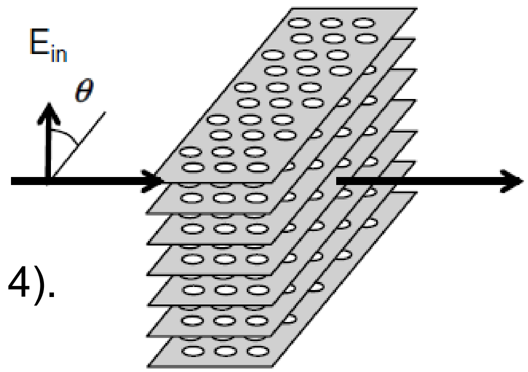
K. Reichel, et al. *Nature Commun.* **9**, 4202 (2018)

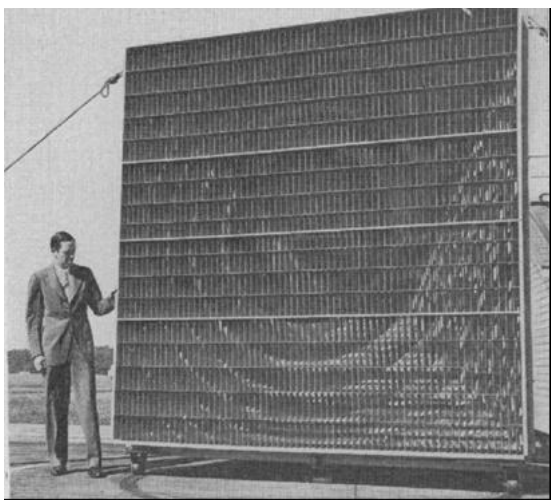
Waveguide stack: an artificial dielectric medium

To overcome issues of 2D optics (out-of-plane diffraction):

A stack of waveguides!

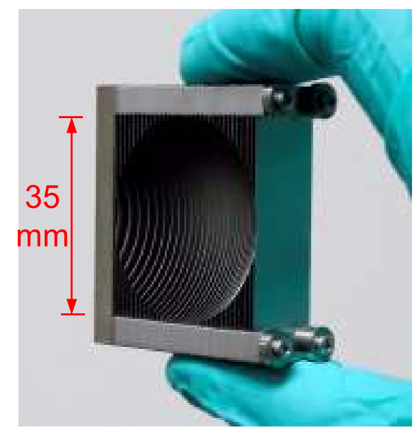
M. Nagai, et al., *Opt. Lett.*, **39**, 146 (2014).





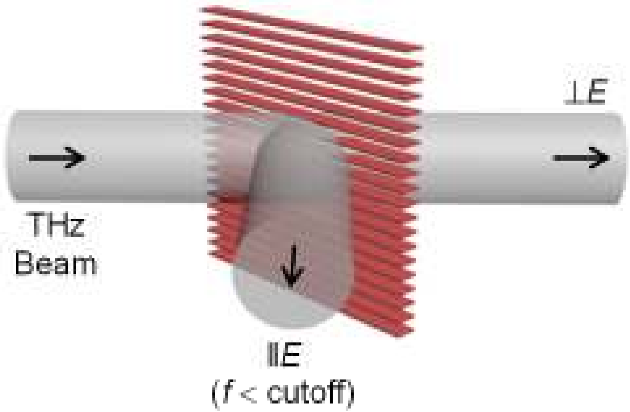
A lens antenna for 4 GHz (ca. 1940)

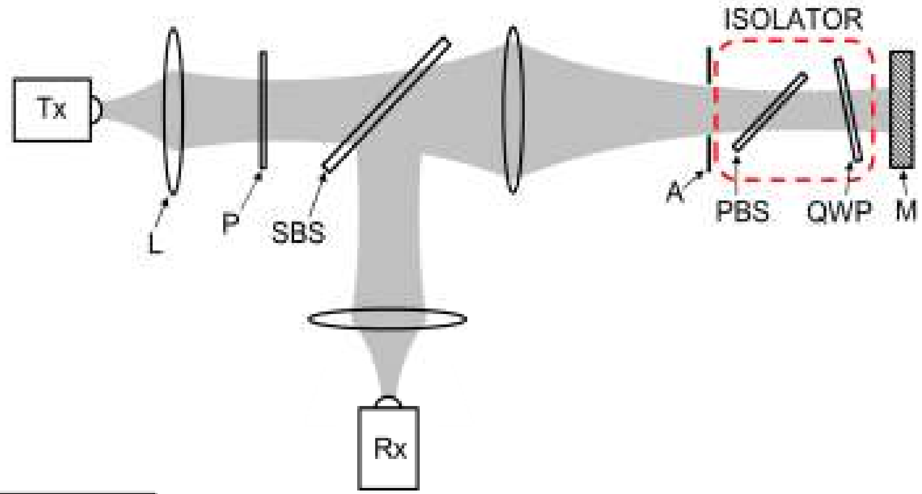
…and for 170 GHz:

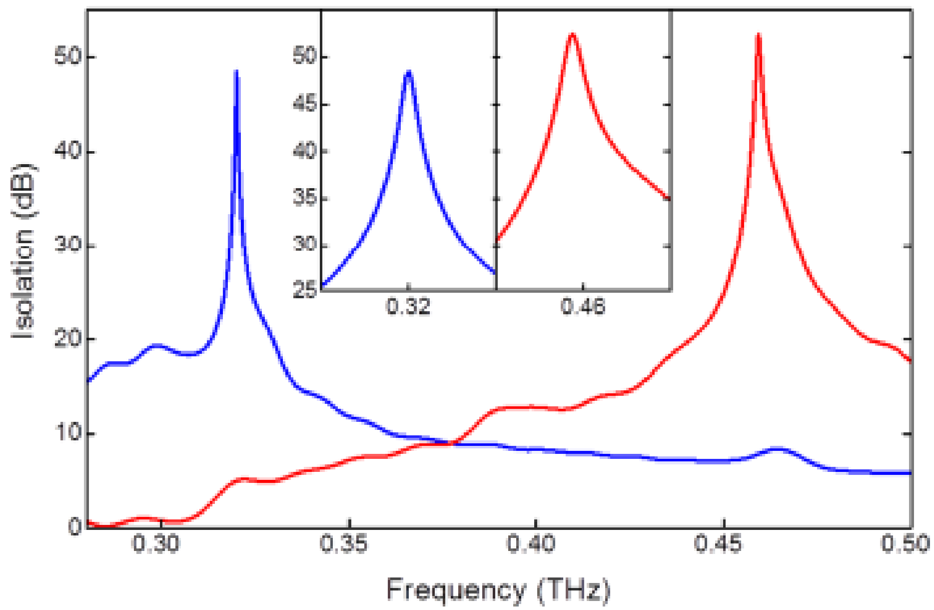


R. Mendis, et al., *Sci. Rep.* 6, 23023 (2016)

Artificial dielectric: a passive isolator





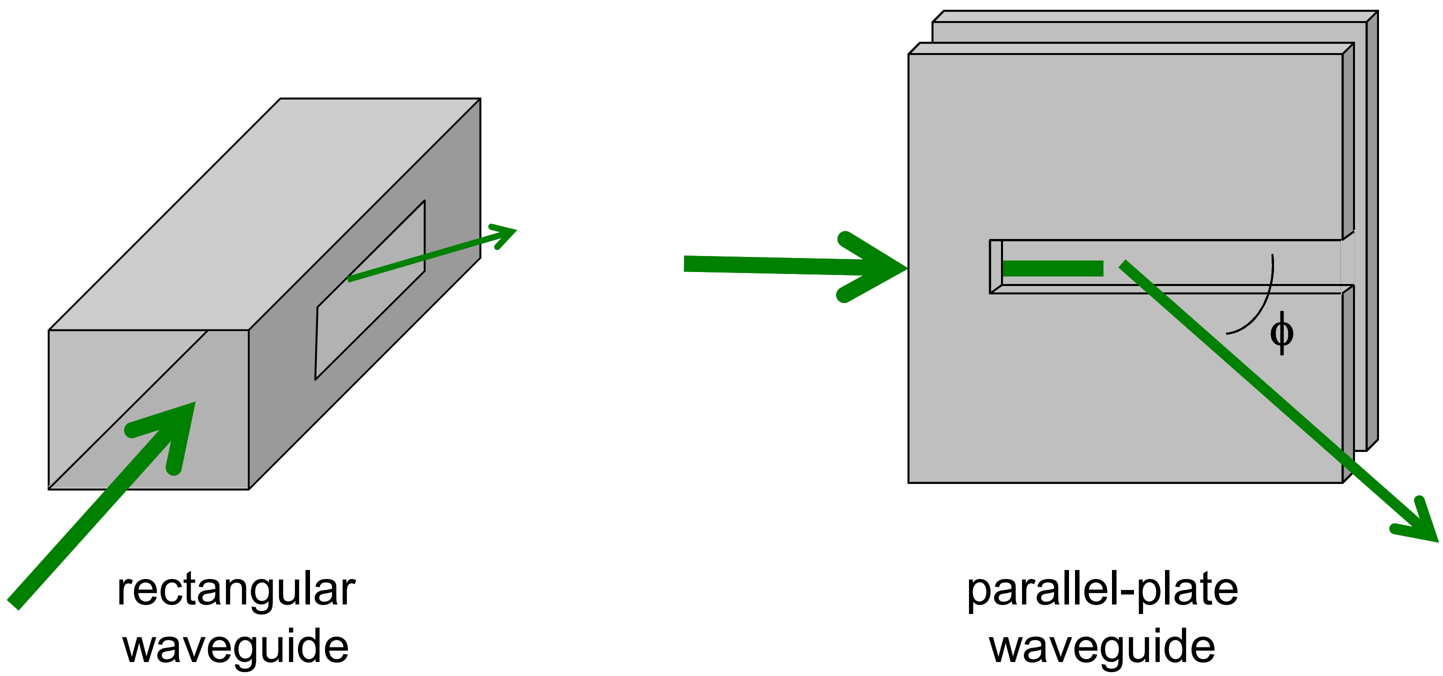


Narrow-band passive isolation of ~50 dB

R. Mendis, et al., *Sci. Rep.*, 7, 5909 (2017).

Leaky wave devices: a candidate for multiplexing

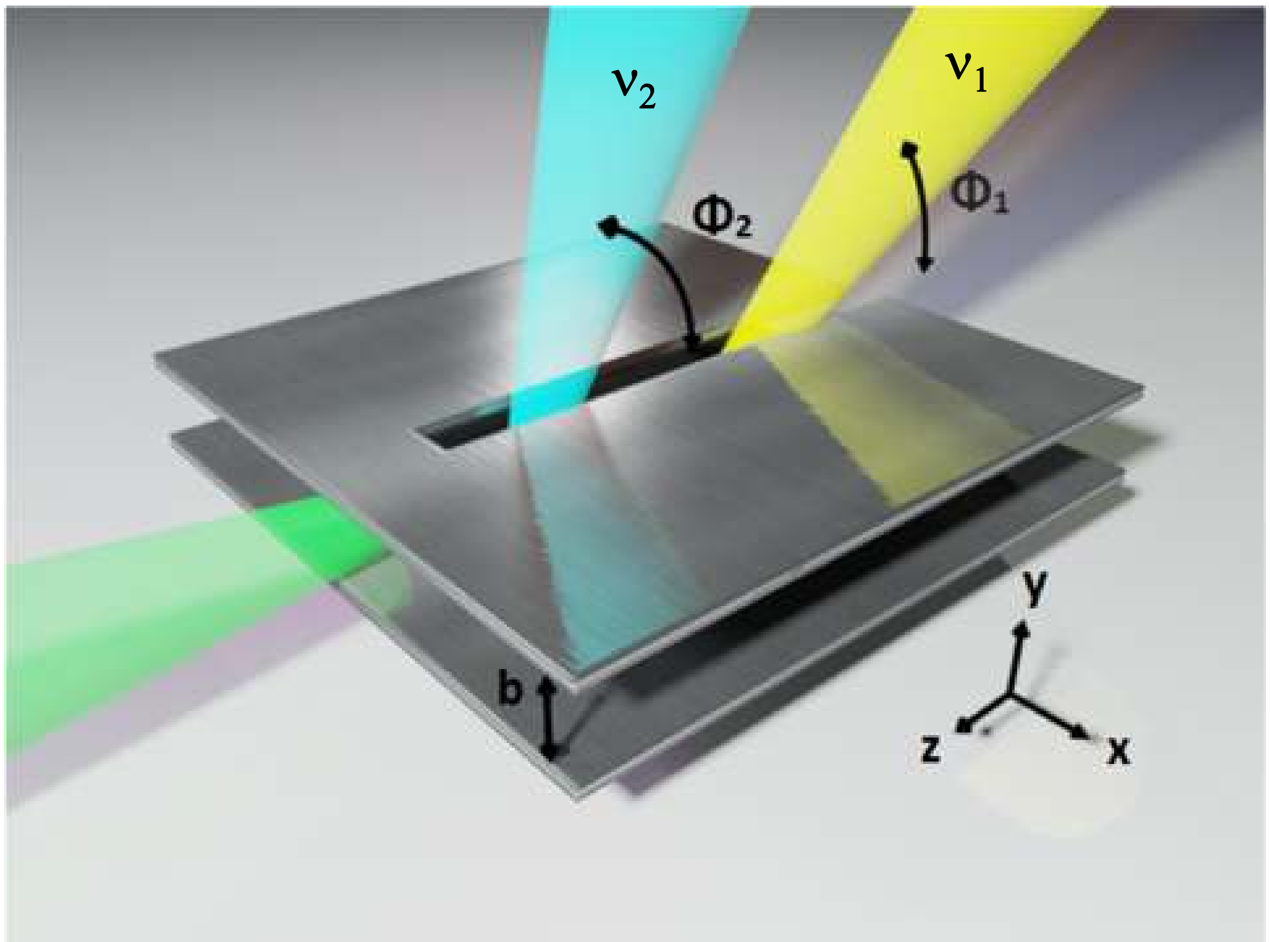
A guided wave device with an opening so that some energy can "leak" out…



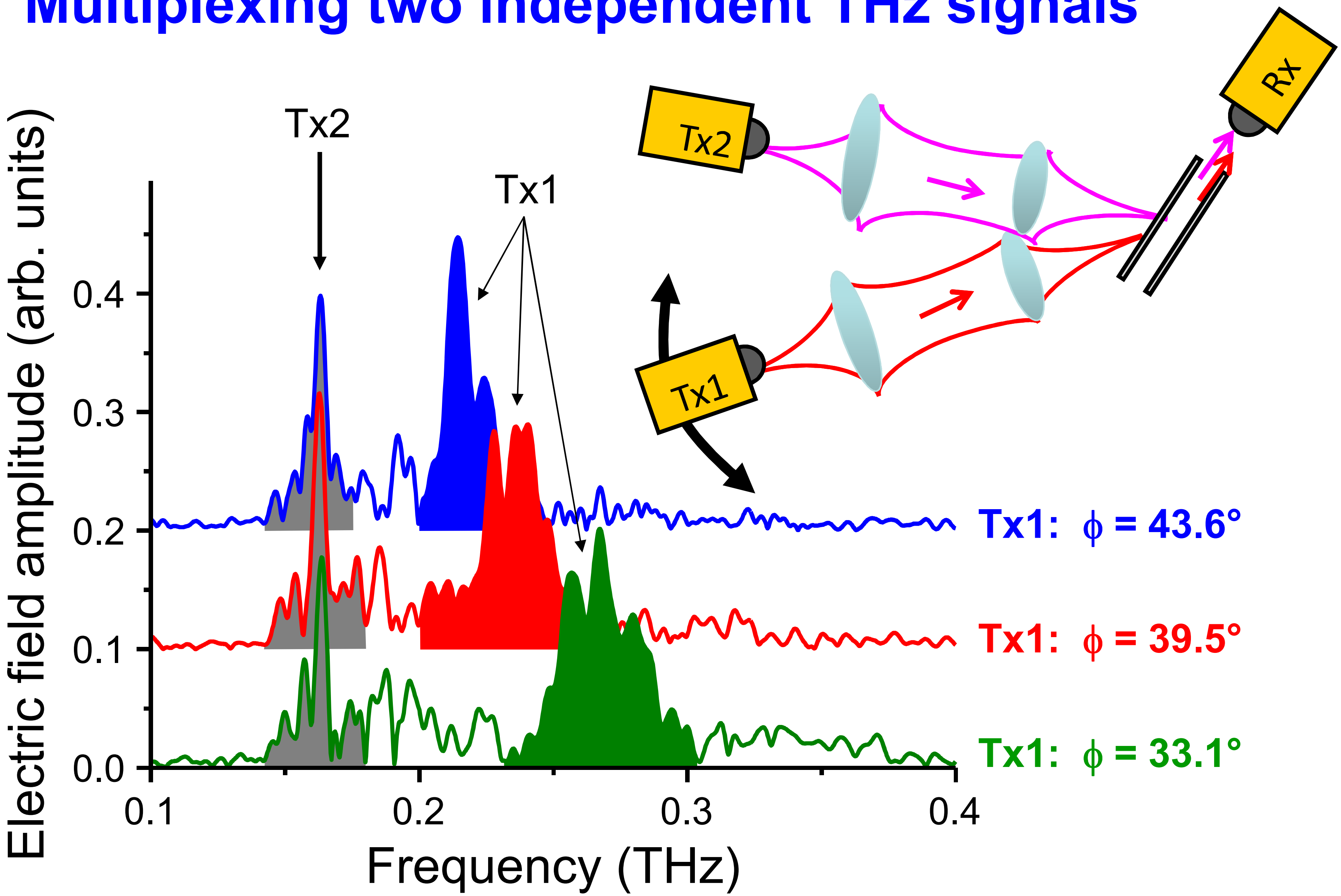
For this to work, the guided mode must be a <u>fast wave</u>, with $v_{phase} > c_0$ → TE waveguide mode

Multiplexing: the idea

Terahertz signals are highly directional. Distinct frequencies can be associated with distinct propagation directions.

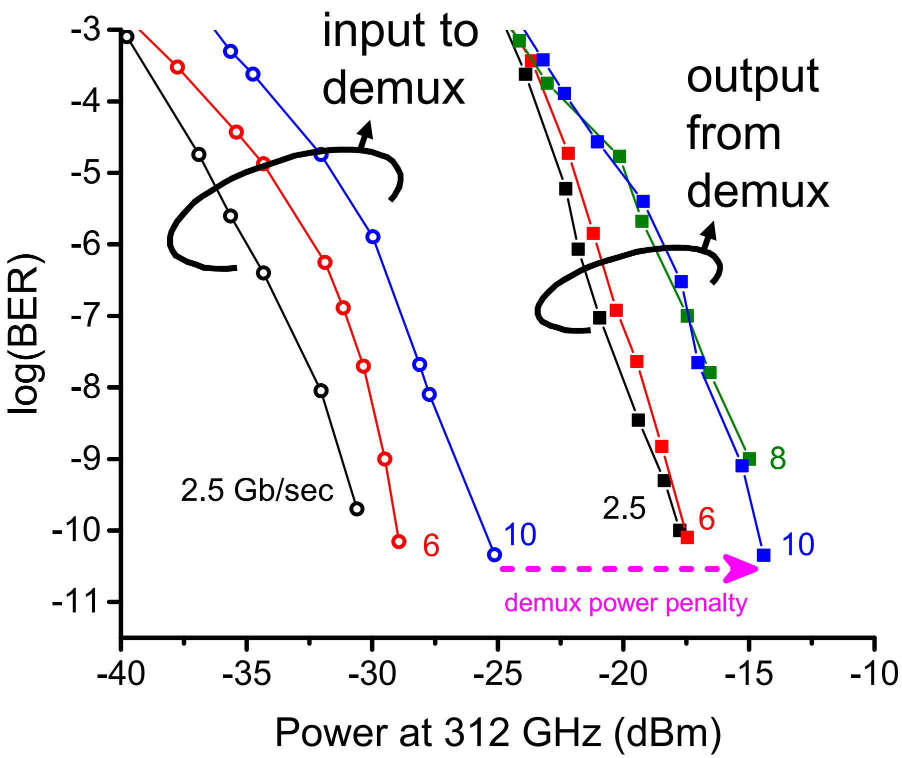


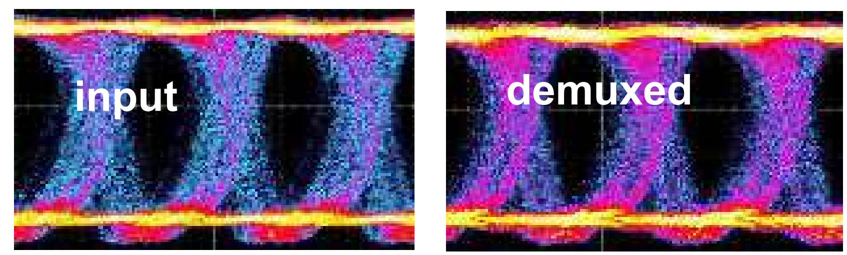
Multiplexing two independent THz signals



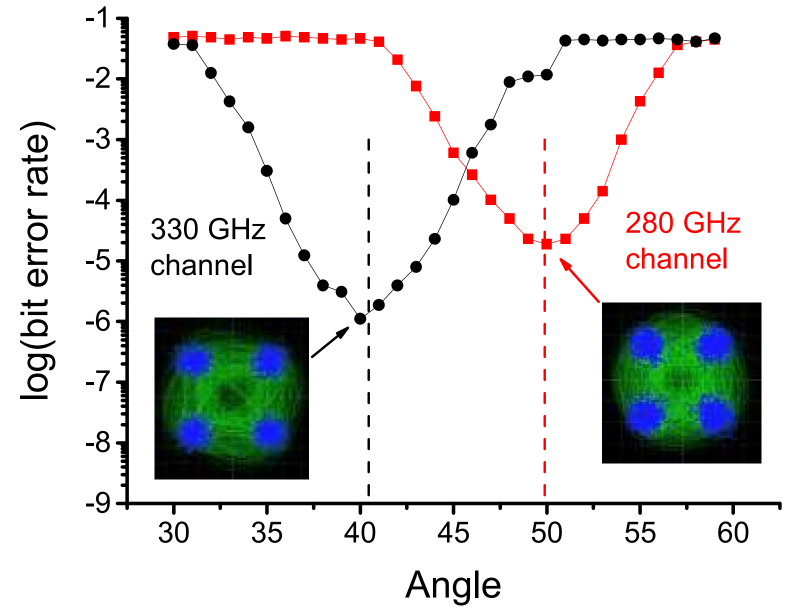
N. Karl, et al., *Nature Photonics*, **7**, 717 (2015)

Multiplexing two independent THz signals



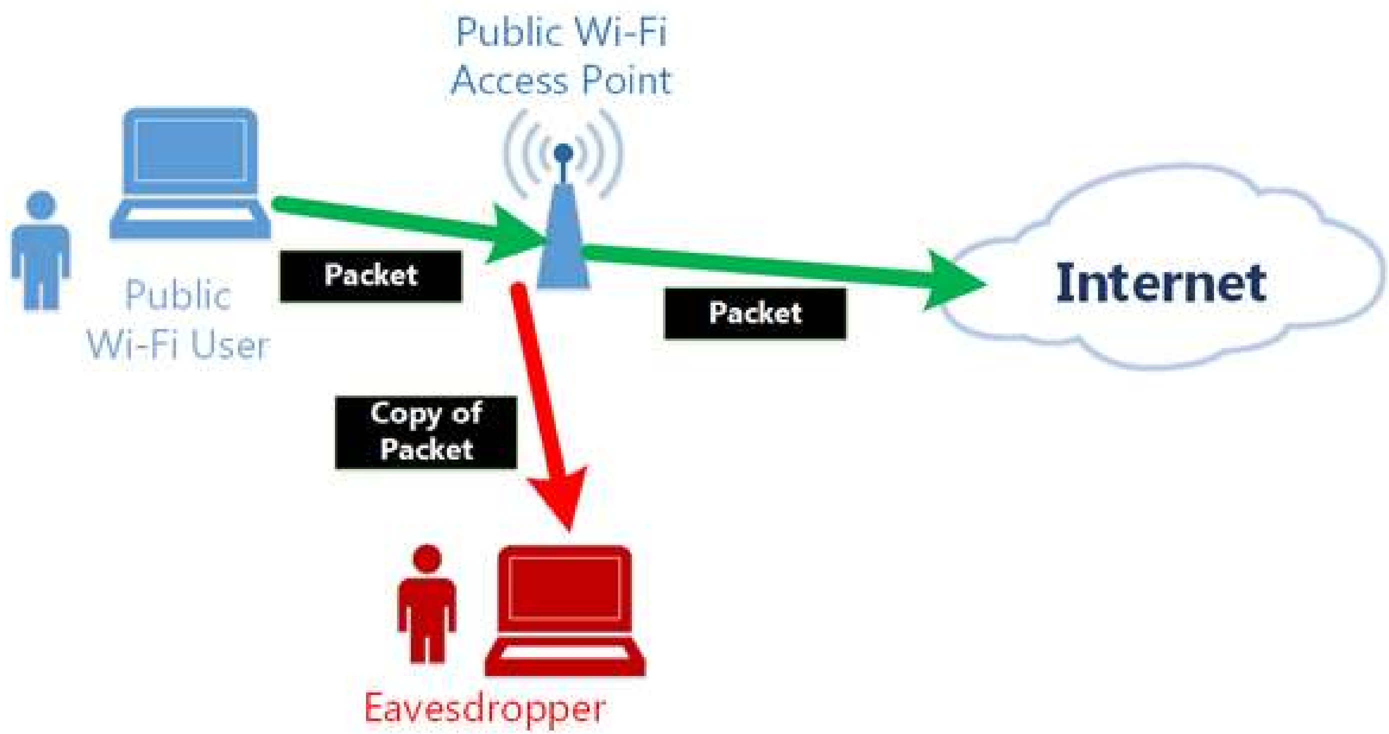


Up to **50 Gbit/sec**!



J. Ma, G. Ducournau, et al., *Nature Commun.* **8**, 729 (2017).

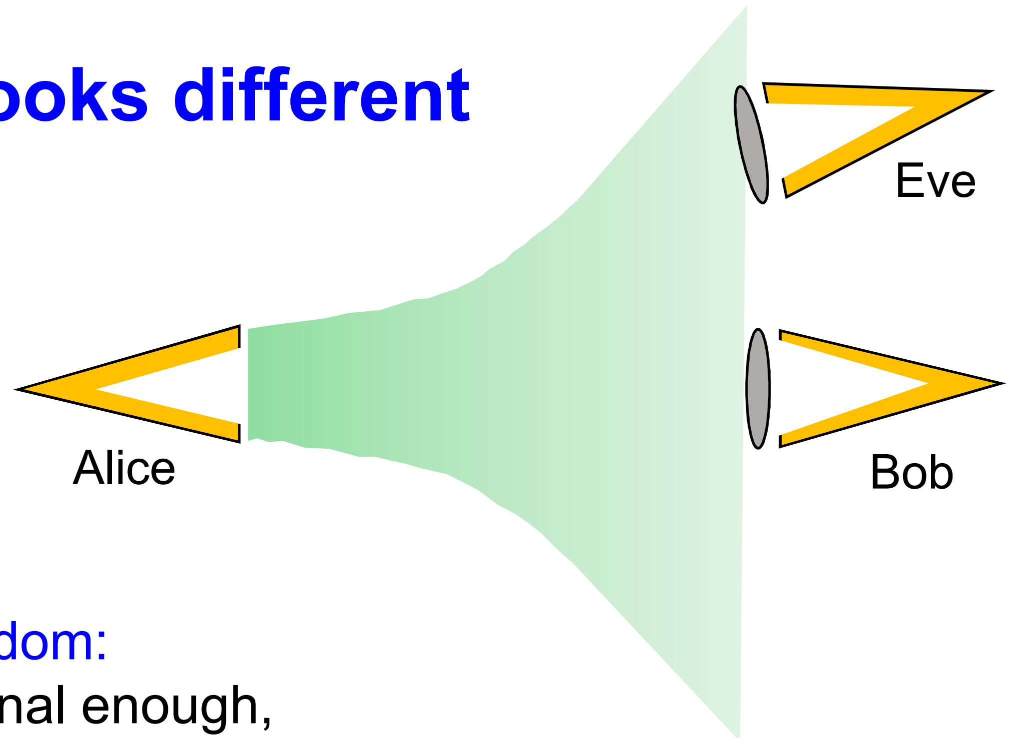
Wireless links: eavesdropping is a concern



Question: How does eavesdropping change if the link is directional?

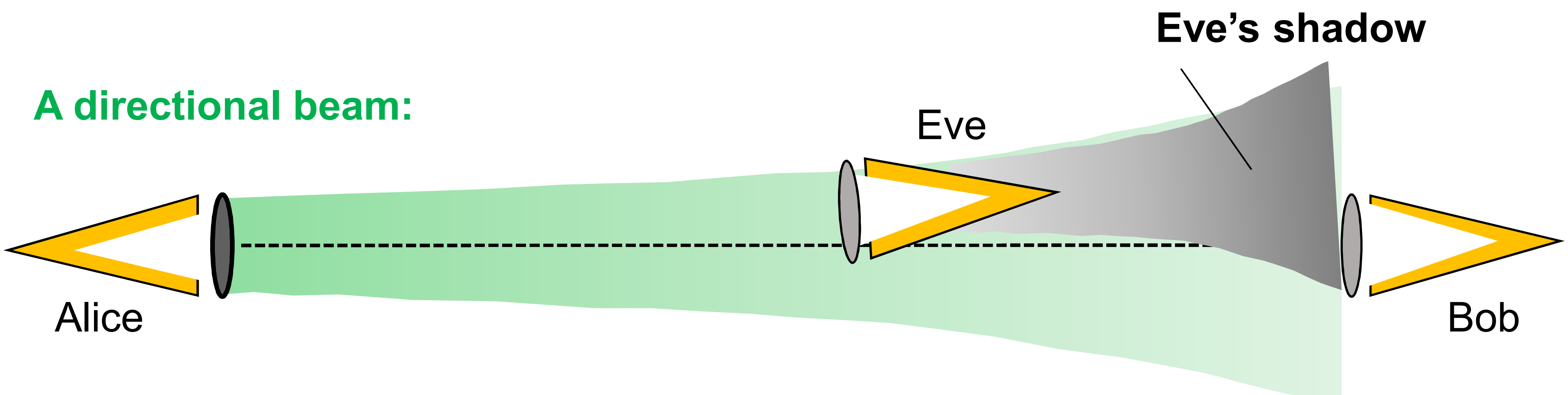
Eavesdropping looks different

A wide-angle broadcast:
(e.g., 120° sector)

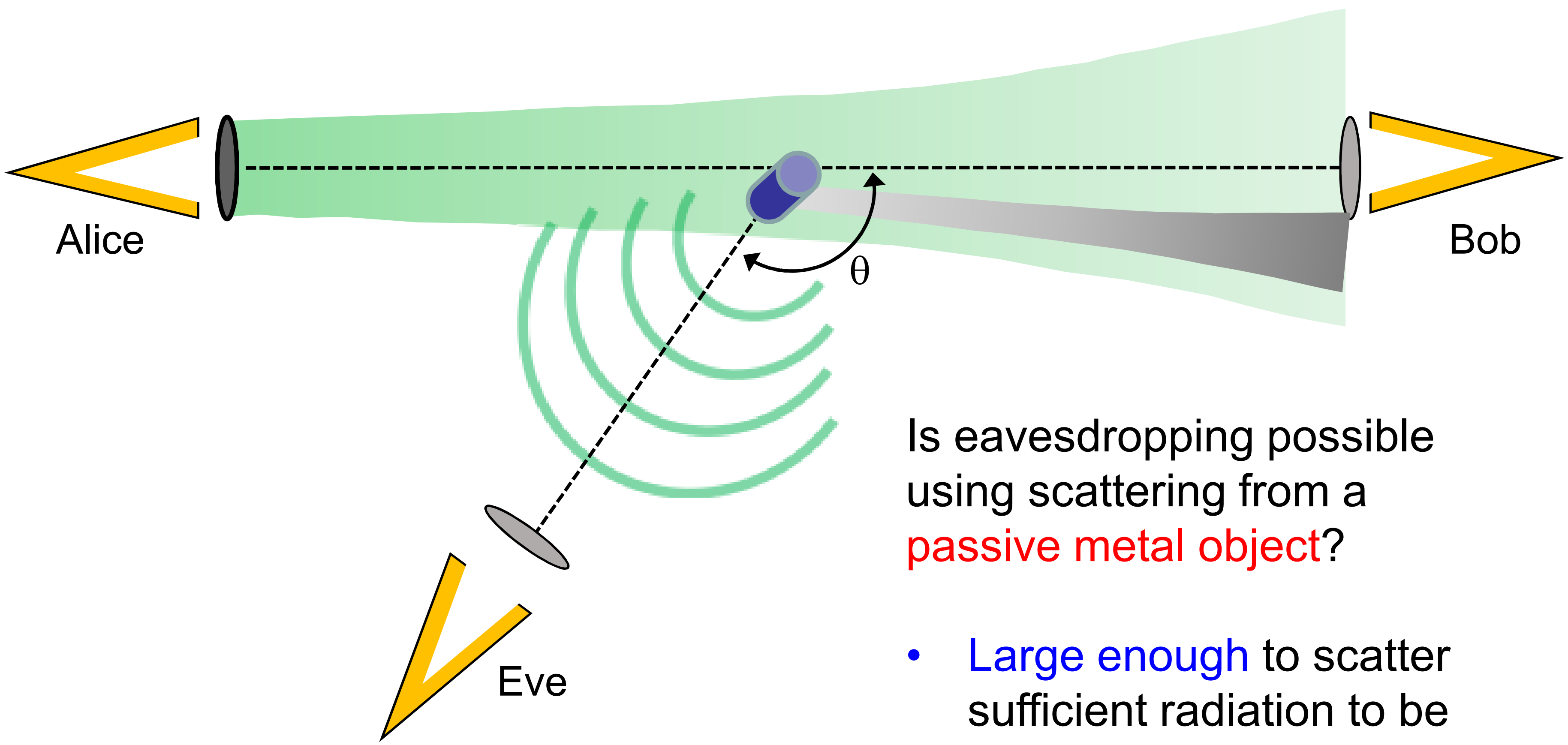


The conventional wisdom:
if the beam is directional enough,
then **Eve will fail** due to blockage of
the intended receiver.

A directional beam:



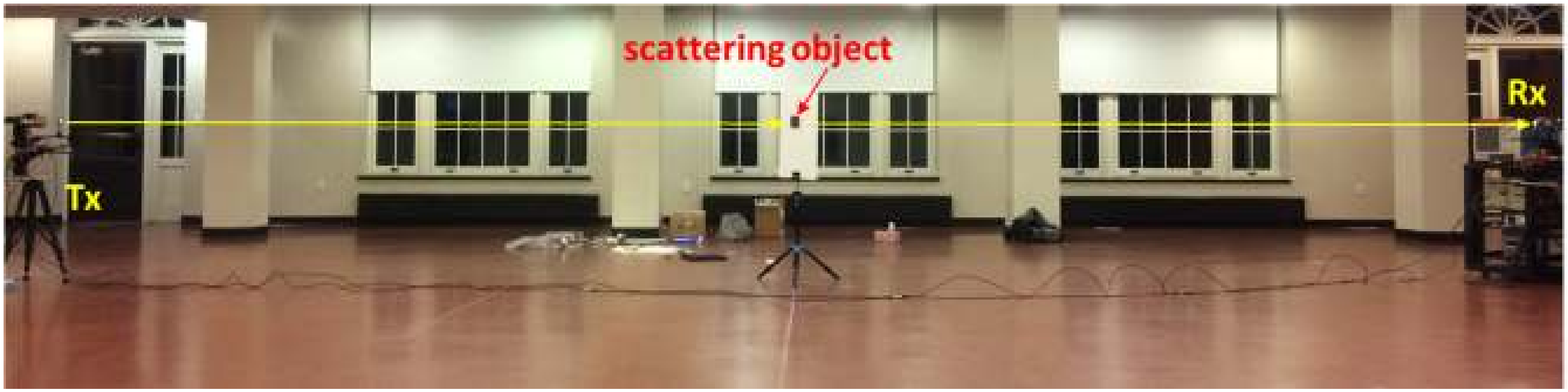
Directional THz links: an alternative strategy for Eve



Is eavesdropping possible using scattering from a passive metal object?

- Large enough to scatter sufficient radiation to be detected
- Small enough to avoid casting a shadow on Bob

Eavesdropping test bed



Flat and cylindrical metallic scattering objects:

Two figures of merit:

- **blockage:** the fraction of Bob's signal that is blocked by the object. A value of zero means:

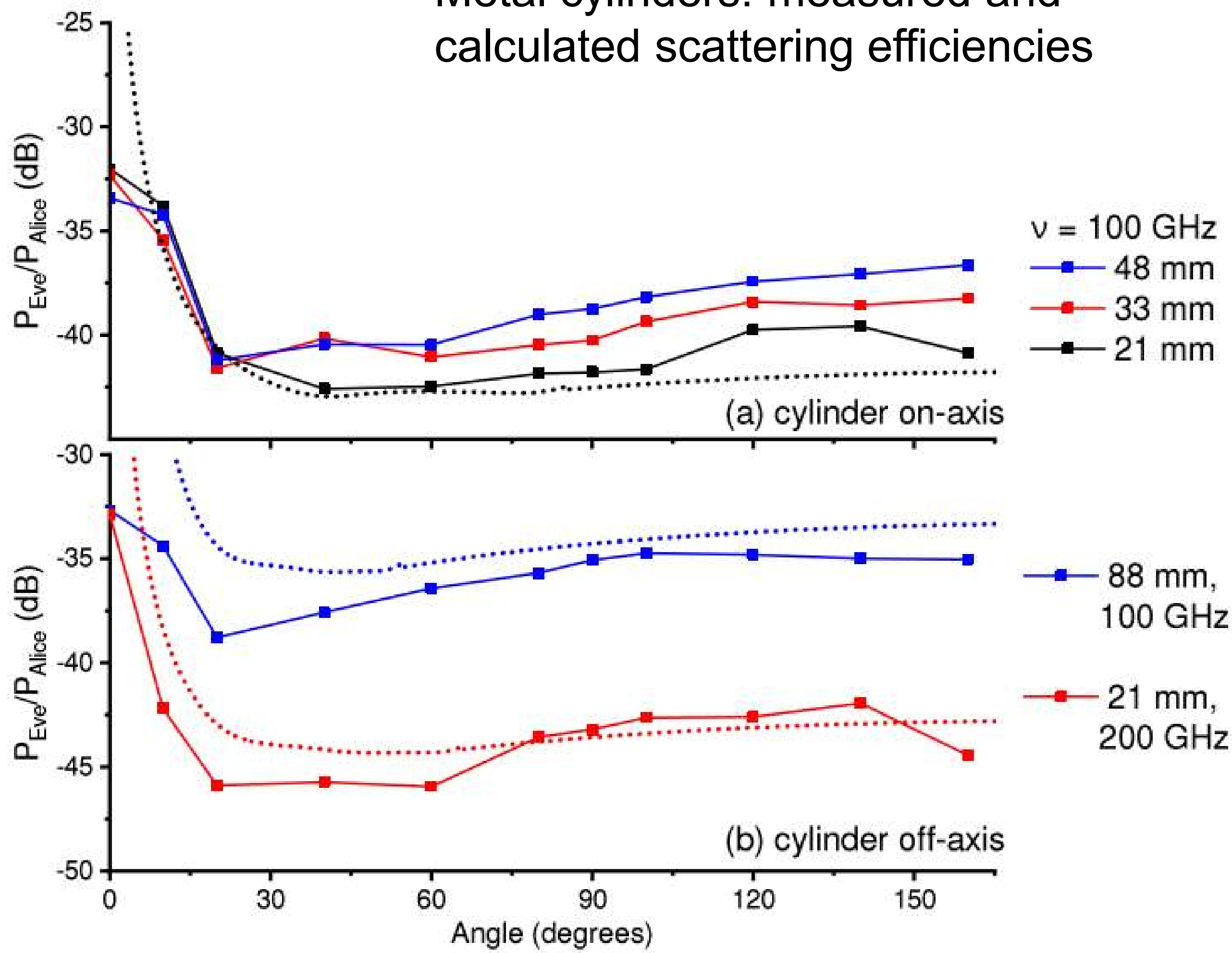
  $\mathrm{SNR}_{\mathrm{Bob}}$ unchanged by Eve

- **secrecy capacity:** how good is Eve's SNR compared to Bob's? A value of zero means:

  $$\mathrm{SNR}_{\mathrm{Eve}} = \mathrm{SNR}_{\mathrm{Bob}}$$

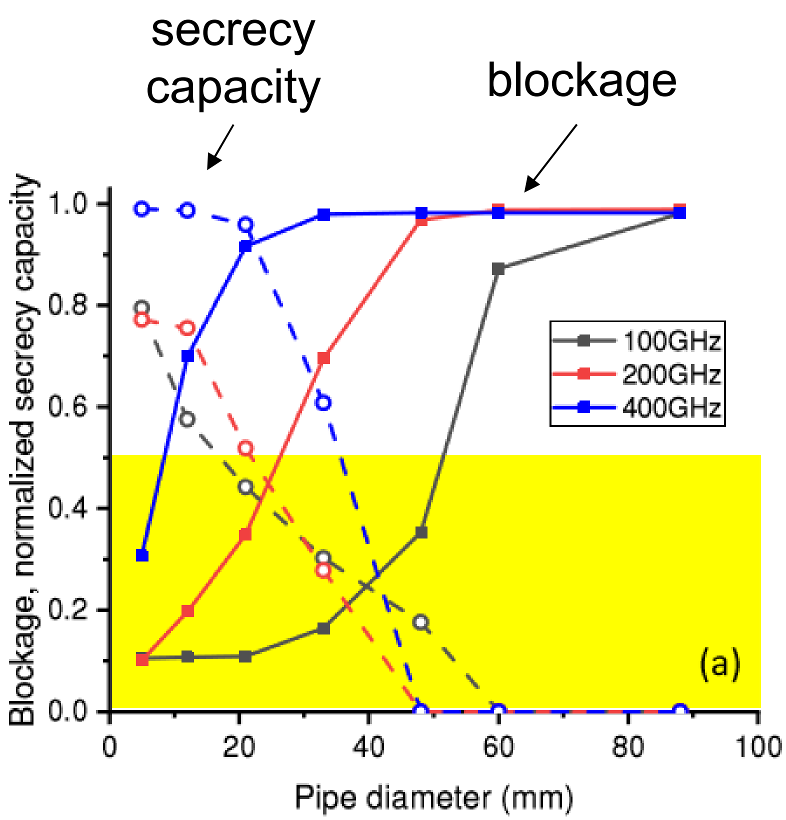
Directional THz links: measuring scattered light

Metal cylinders: measured and calculated scattering efficiencies

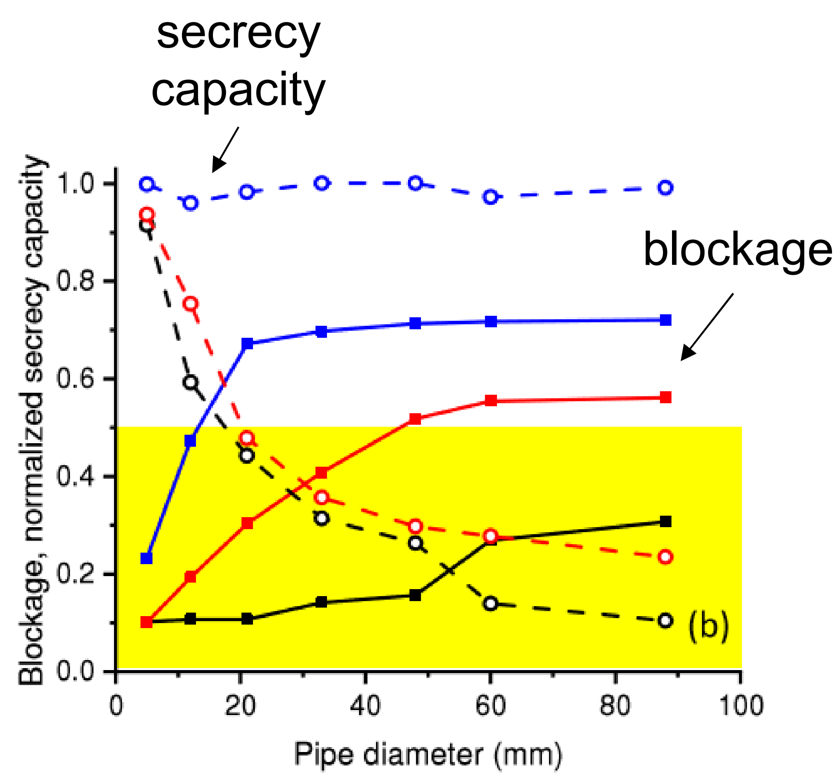


J. Ma, et al., *Nature*, **563**, 89 (2018)

Directional THz links: blockage, secrecy capacity



On axis

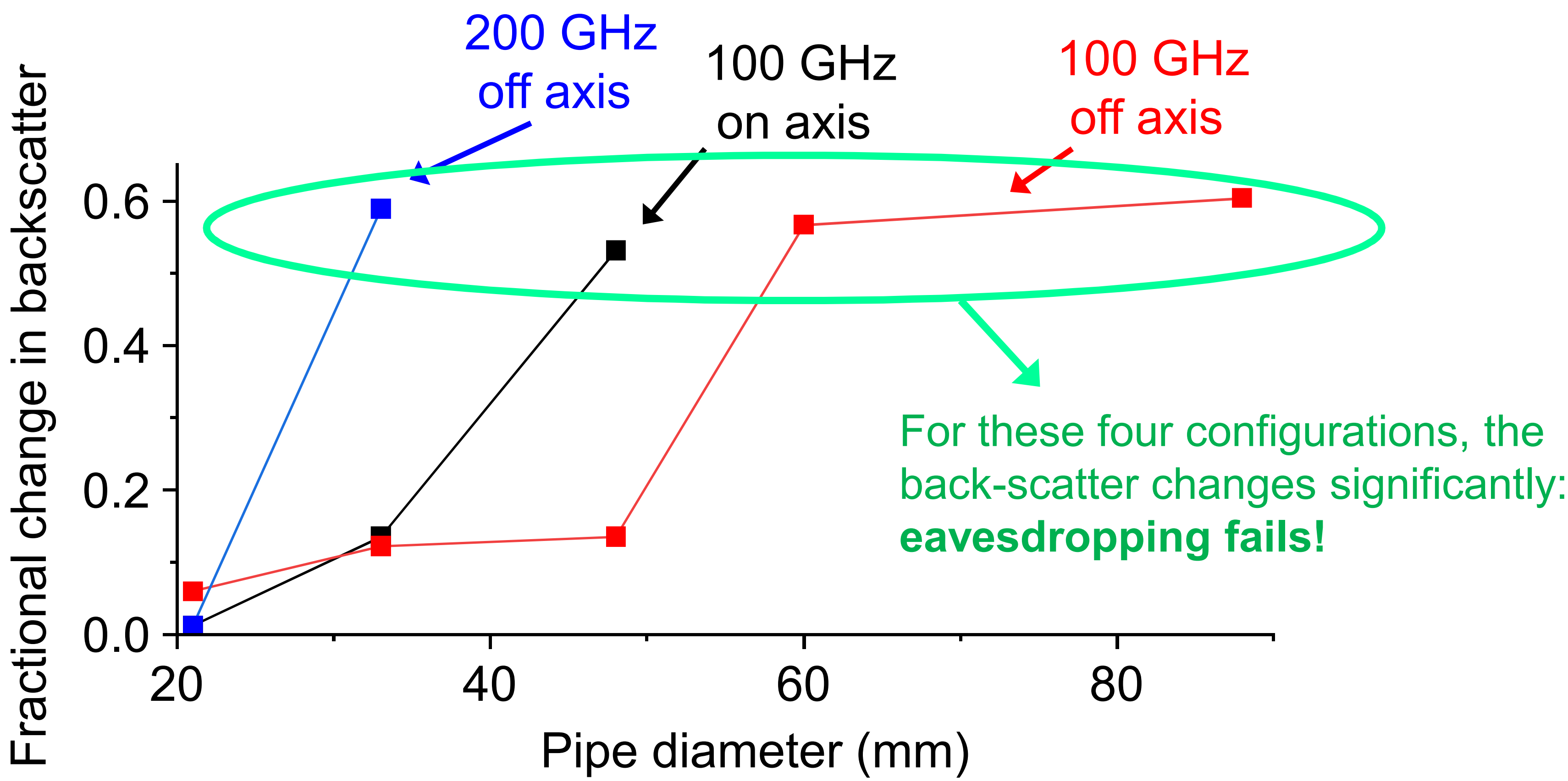


Off axis

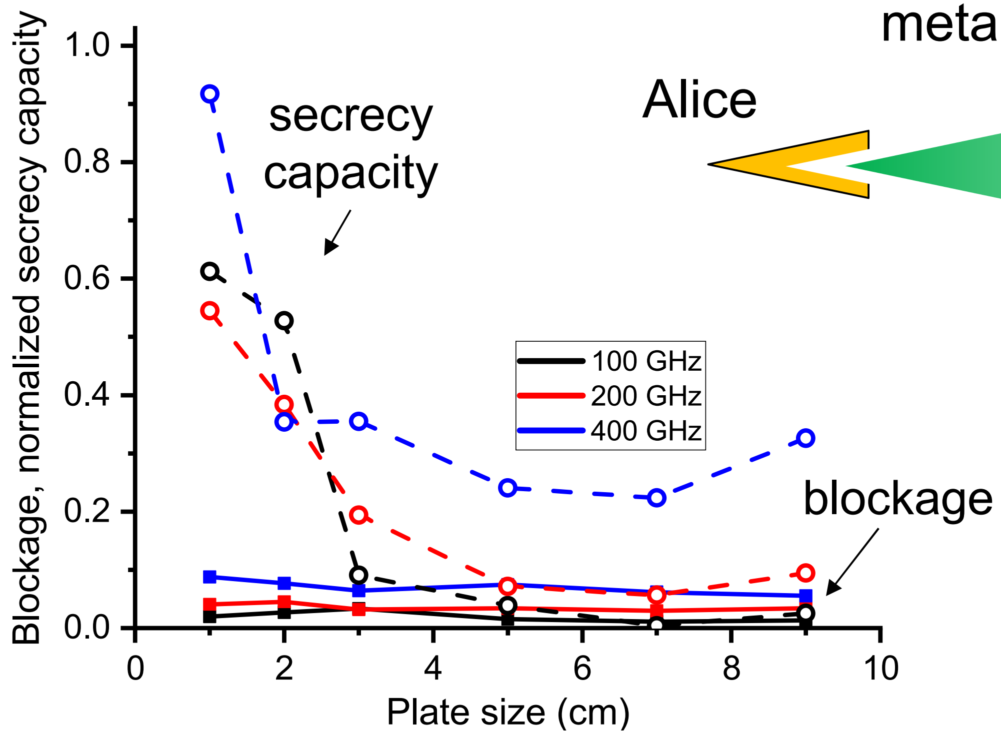
J. Ma, et al., *Nature*, **563**, 89 (2018)

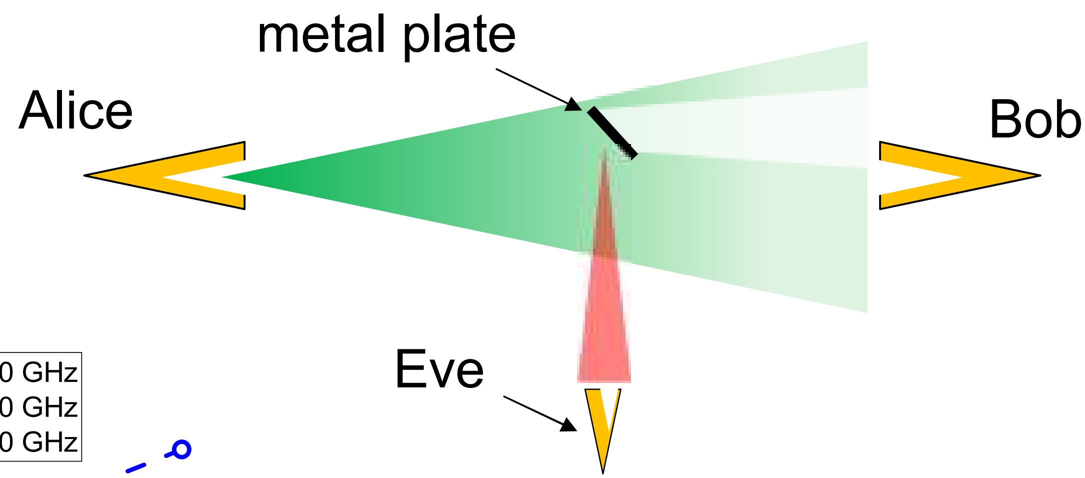
A counter-measure

Suppose Alice has a transceiver (not just a transmitter), and can monitor the back-scatter from the channel.



Directional THz links: blockage, secrecy capacity





Metal plates: even more effective (although Eve has less freedom)

A clever eavesdropper always wins.
(although less easily at higher frequencies)

J. Ma, et al., *Nature*, **563**, 89 (2018)

Conclusions

- THz communications: **many** challenges remain

- THz links: this is not merely 'microwaves with a few extra zeros.' Things are fundamentally different.

- Channel characteristics: there is still a lot of 'conventional wisdom' that needs correcting.

- Borrowing ideas from optics is very inspiring!

Funding: