Integrated optics developments for the 3-5µm mid-infrared range

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Acknowledgments: Jan Tepper, Romina Diener, Stefano Minardi, Robert Thomson, Alexander Arriola, Stefan Nolte, Airan Rodenas, Guillermo Martin, Ajoy Kar, Pierre Kern, Bruno Lopez, Jorg-Üwe Pott, Thomas Henning, Jean-Philippe Berger, Ben Bernacki, Simon Gross, Norman Anheier, Robert Harris, Roger Haynes, Nem Jovanovic, Mike Withford

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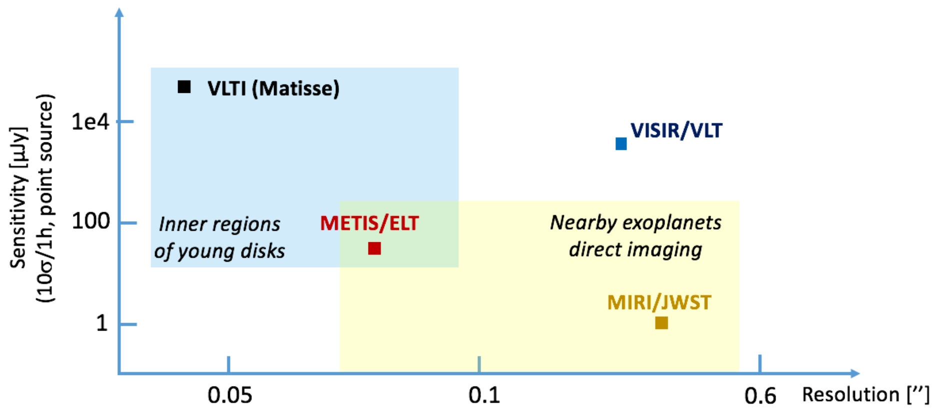
Context and interest in Hi-5

- Importance of the **mid-infrared range** for the study of planet formation, circumstellar disks, sub-stellar objects, exoplanets, AGNs
- **MATISSE** will reach highest resolution
- At the VLTI, 6-telescope array increase efficiency and **image fidelity**
- **High-dynamic range** capabilities critical for science on disks and exoplanets
- Background of GRAVITY, PIONIER experience using **integrated optics**

→ **High-precision** interferometry thanks to wavefront filtering and single-mode operation

→ System **miniaturization**. Highly stable instrumental transfer function. Cryogenics.

→ Interest for the **L, M** bands



Objectives and collaborations

- Experimental **validation** and **characterization** of integrated optics (IO) interferometric functions for the 3-12 μm
- **Proof of concept**, parameter/design optimization, optical **performances** compatible with **scientific requirements**

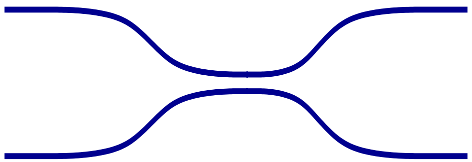
→ *Contribute IO-based instruments for high-precision interferometry/imaging in the mid-infrared*

Heriot-Watt Univ./Grenoble group	Univ. Jena/AIP Potsdam	Group M. Withford (Macquarie, Sydney)
(e.g. Rodenas et al. 2012; Arriola et al. 2014; Labadie et al. 2011, 2012)	*(e.g. Tepper et al. 2017a; Diener et al. 2016, 2017; Errmann et al. 2015; Labadie+Minardi 2016) / ALSI-BMBF & NAIR-DFG projects*	*(e.g. Tepper et al. 2017b)*

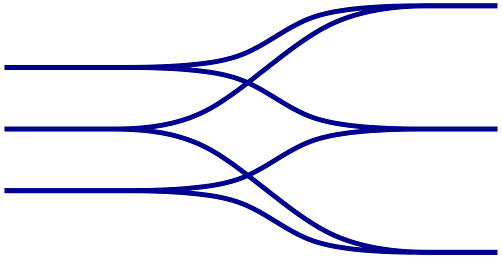
Strategy of work/Investigated functions

- Among different technological platforms (cf. Labadie+ 2009), **laser writing** is a promising one to manufacture integrated optics in mid-infrared dielectric substrate
- Platform well adapted to the **low-volume production** in astronomy
- **Versatile** platform tested on a large variety of glasses

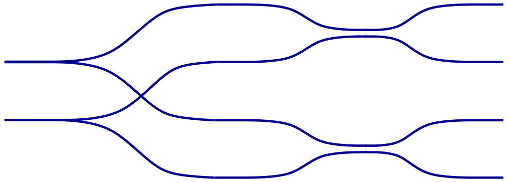
Symm./Asymm. coupler (Tepper 2017)



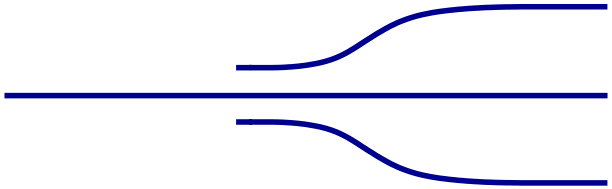
Pair/wise combiner (Rodenas 2012)



Static ABCD (Diener 2017)

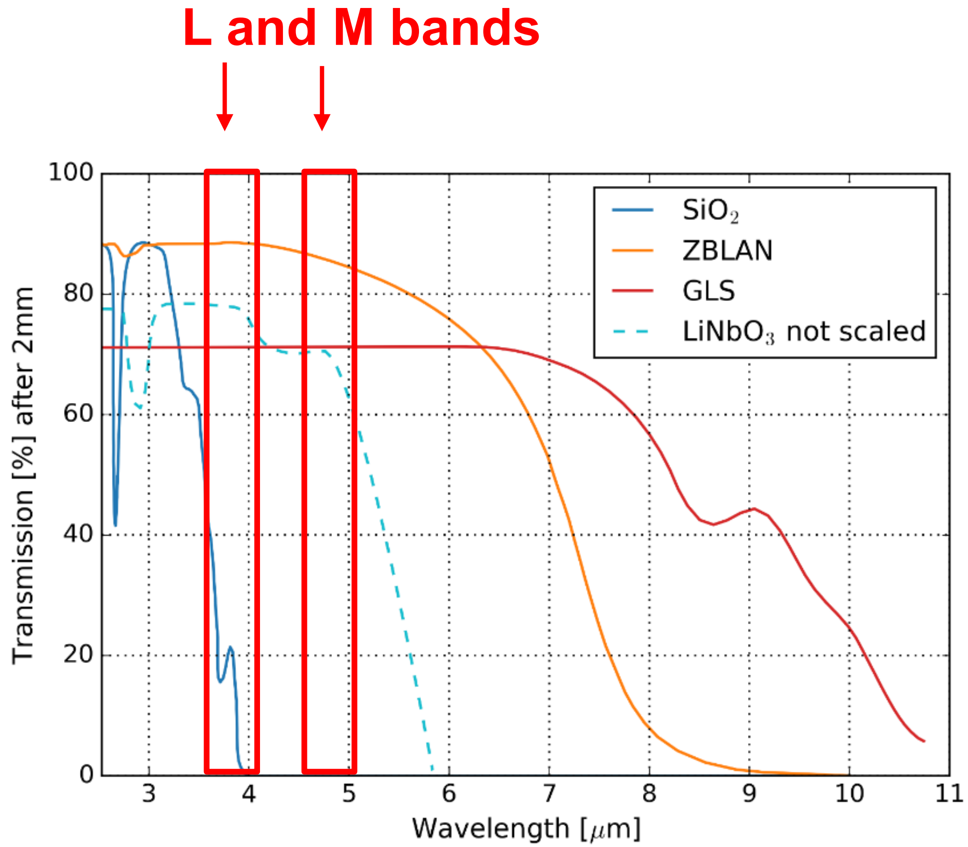


tricoupler



Choice of suitable materials

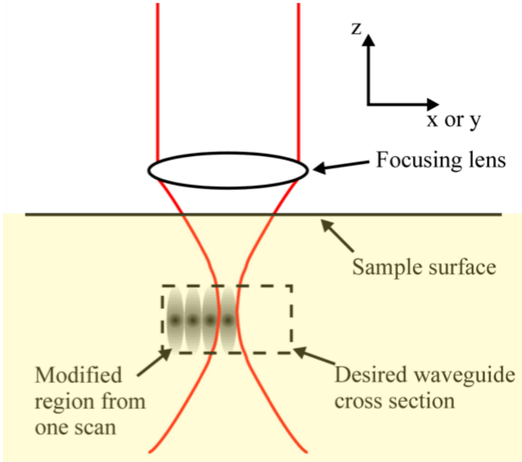
- Current operational IO astronomical instruments below 2.4µm (GRAVITY, PIONIER)
- Goal: extend IO operation to longer wavelengths
- Exploring different materials and different technologies
- **Chalcogenide (GLS) Fluoride (ZBLAN) glasses are interesting options for the mid-IR**



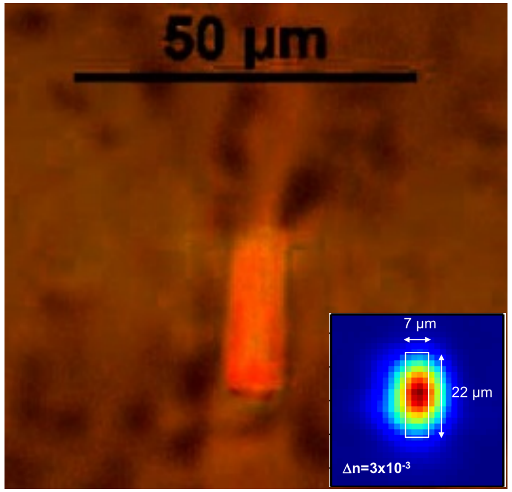
Transparency for SiO_2, ZBLAN (*Parker* 1989), GLS[1] and LiNbO[3] [2] (y-axis not scaled)
(includes Fresnel reflection)

Laser-writing platform

- Femtosecond laser induces permanent structural change of the refractive index
- Confined index variation→ waveguide
- Versatile and "low-cost" technological platform
- 3-D capabilities depends on NA of focusing lens

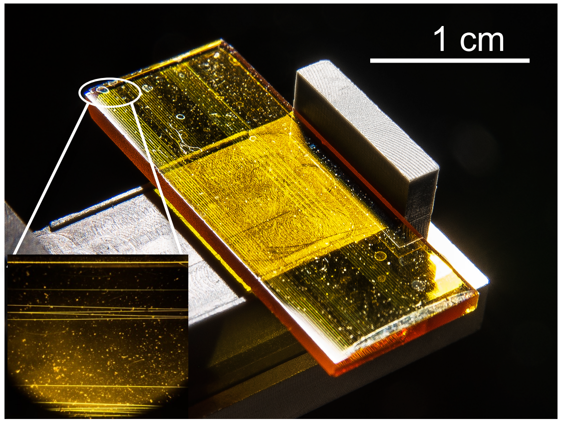


(Cf. Review Gross & Withford 2015)



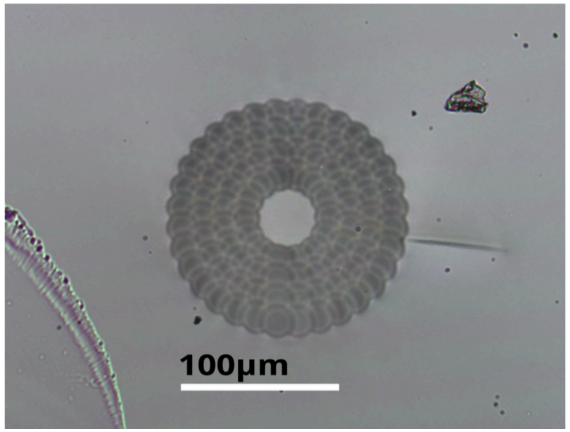
(Diener 2017)

ULI waveguides in GLS



(Tepper 2017)

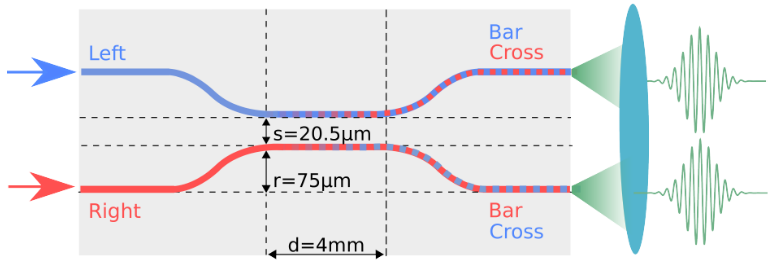
Depressed cladding in ZBLAN

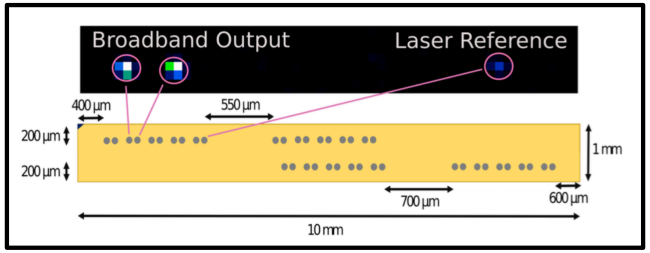


(courtesy S. Gross; Tepper 2017b)

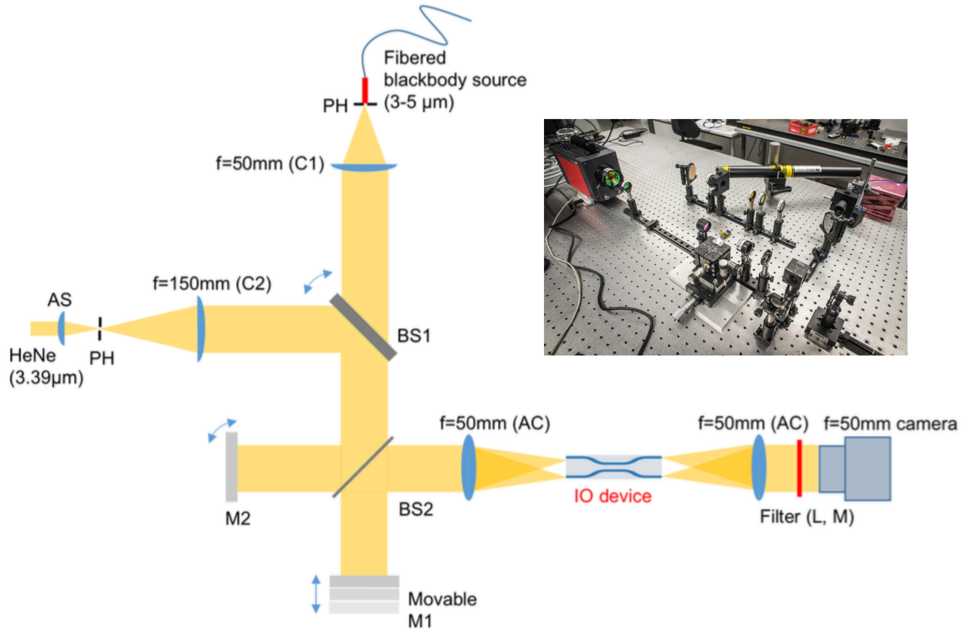
Key performance parameters

- Key parameters for characterization

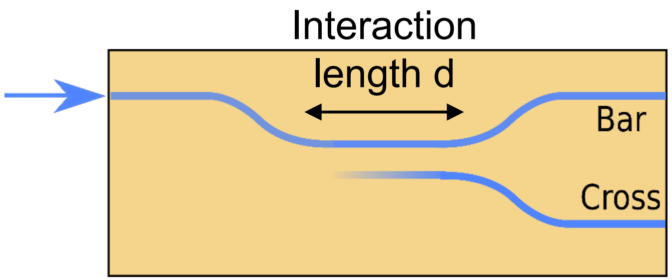


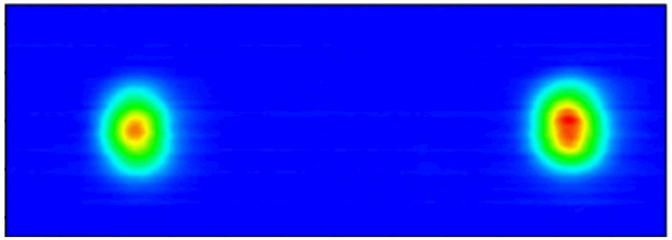


Property
Integrated splitting ratio
Spectral slope for splitting ratio
Differential birefringence
Phase variation (diff. dispersion)
Interferometric contrast
Modal behavior
Propagation/bending losses
Total throughput

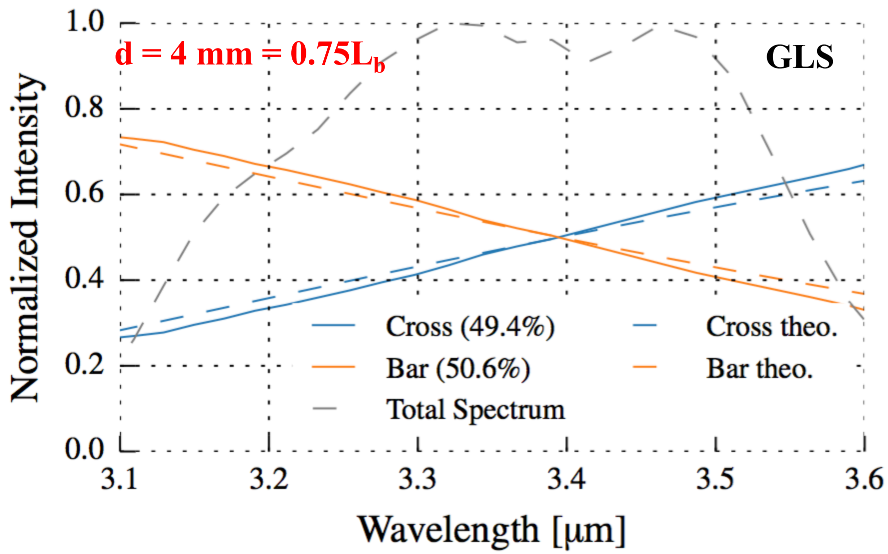


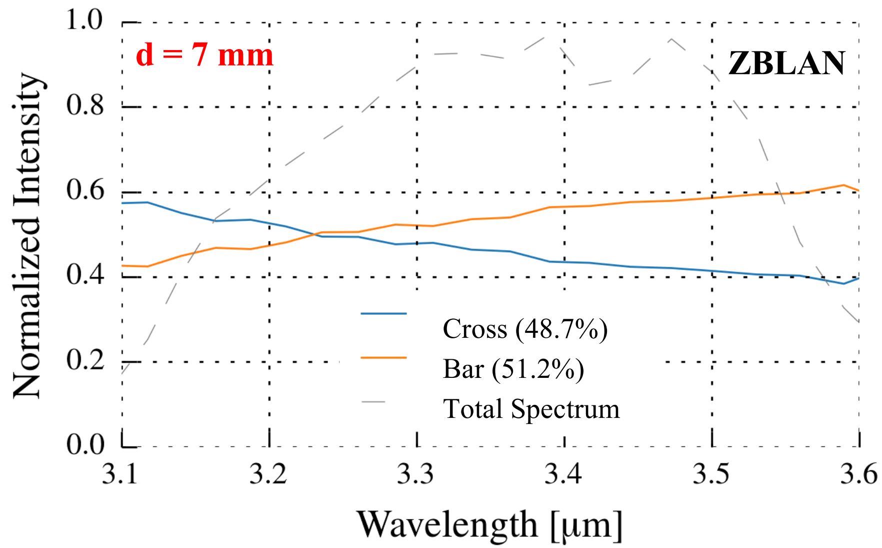
Beam combiner chromaticity





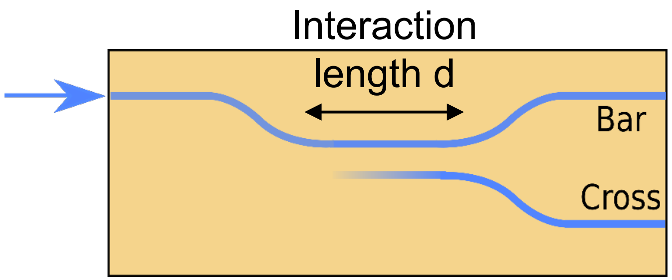
$$P \propto \sin(K.d/\lambda)^2$$

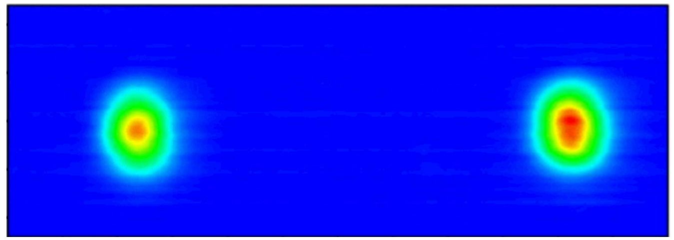


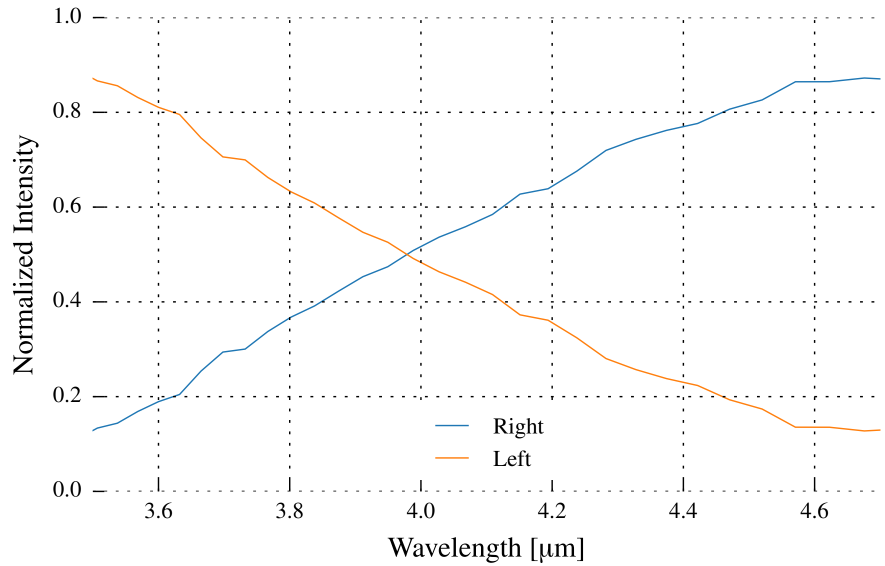


→ Splitting asymmetry leads to contrast loss of ~1% to 2.5% in broadband

Beam combiner chromaticity







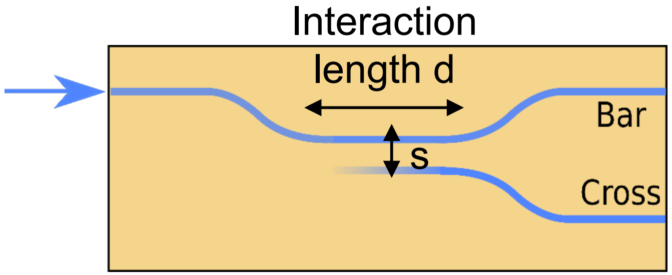
d = 0 mm

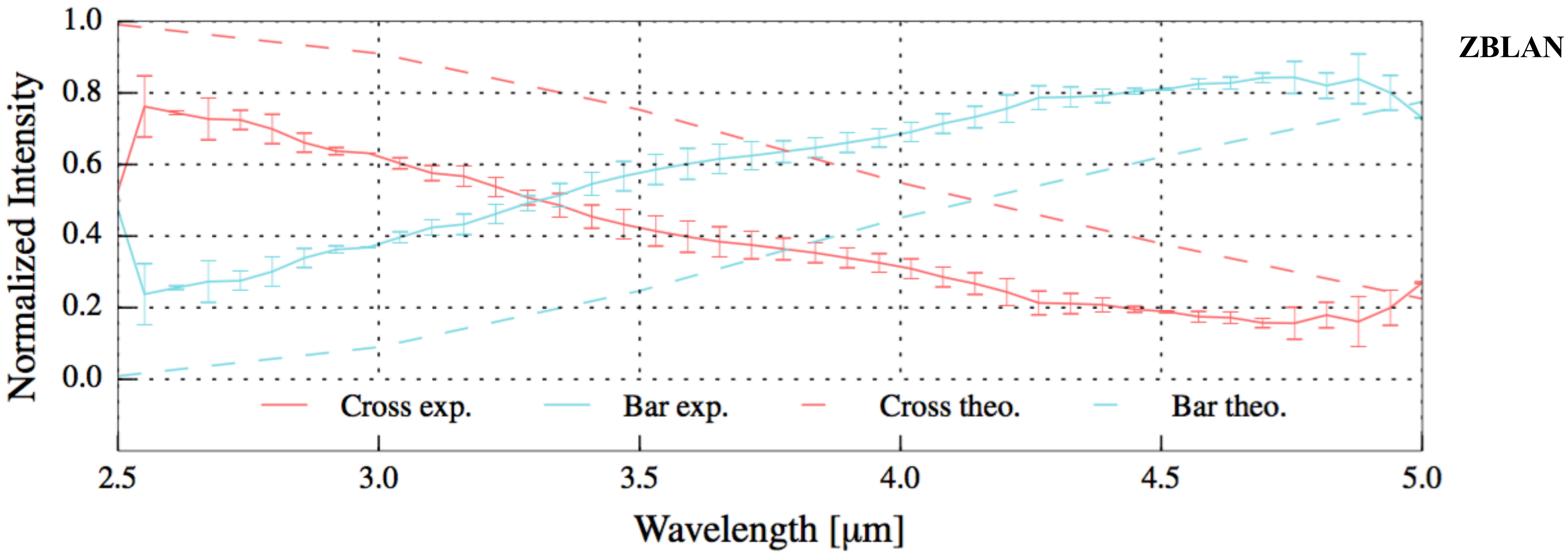
s = 21 μm

GLS

→ Splitting asymmetry leads to contrast loss of ~1% to 2.5% in broadband

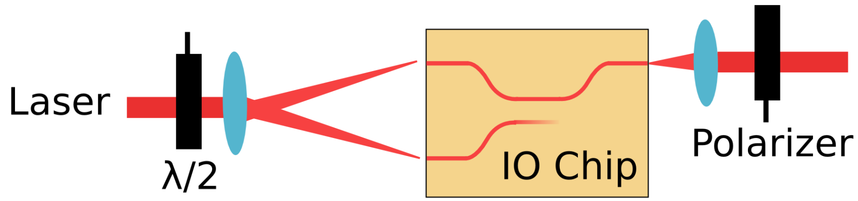
Beam combiner chromaticity

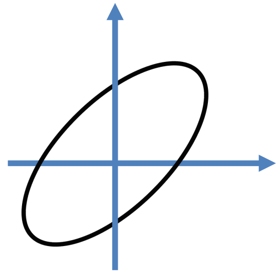




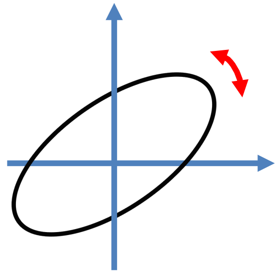
- ZBLAN coupler with Δn =-7x10^{-4}
- Design center-to-center separation **s** = 39.9 μm (experimental **s** = 36 μm)

Differential birefringence



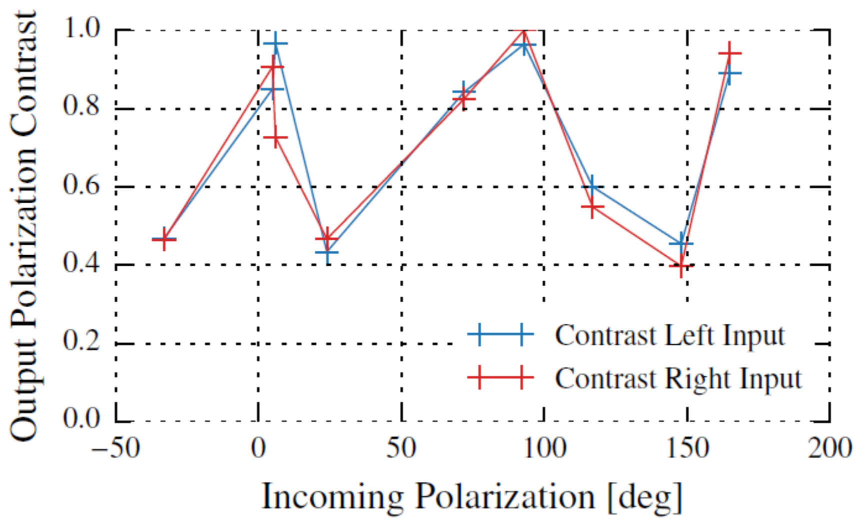


From Input 1

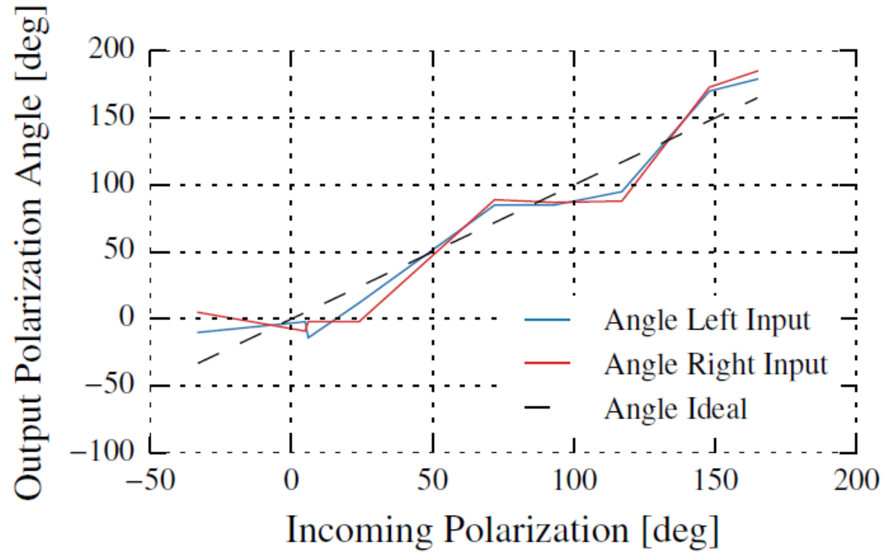


From Input 2

Change in polarization state (linear-> elliptical)



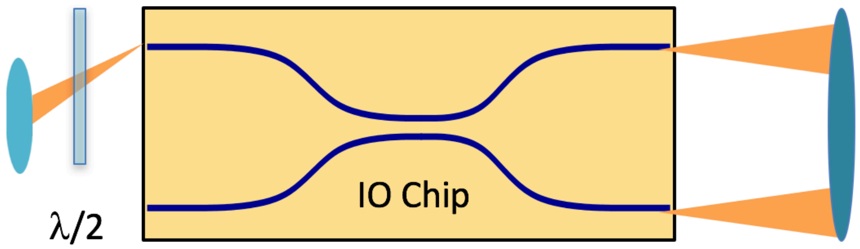
Change in polarization angle



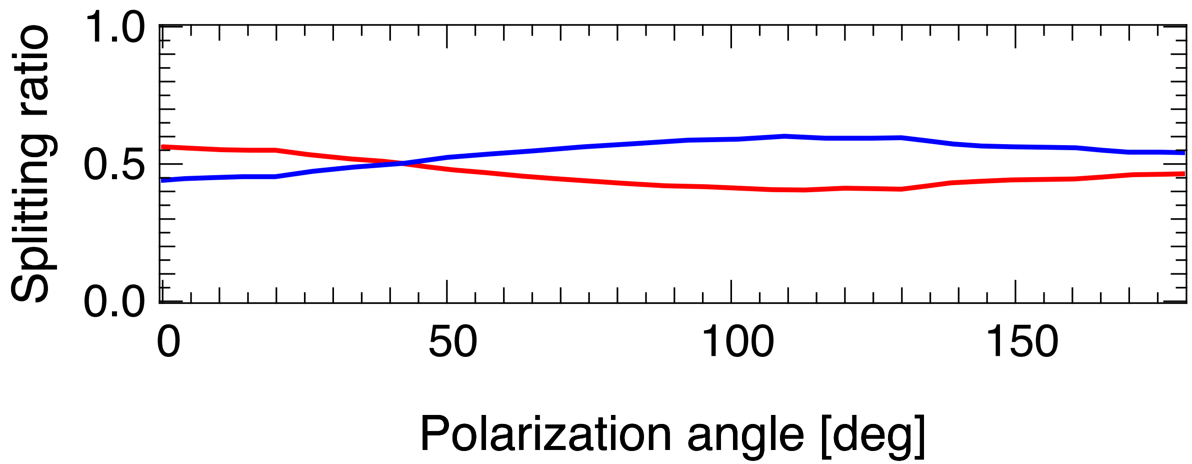
→ Polarization altered in comparable strength for both inputs

→ Measured impact on the interferometric contrast: decrease of 1.4%

Splitting ratio vs input polarization

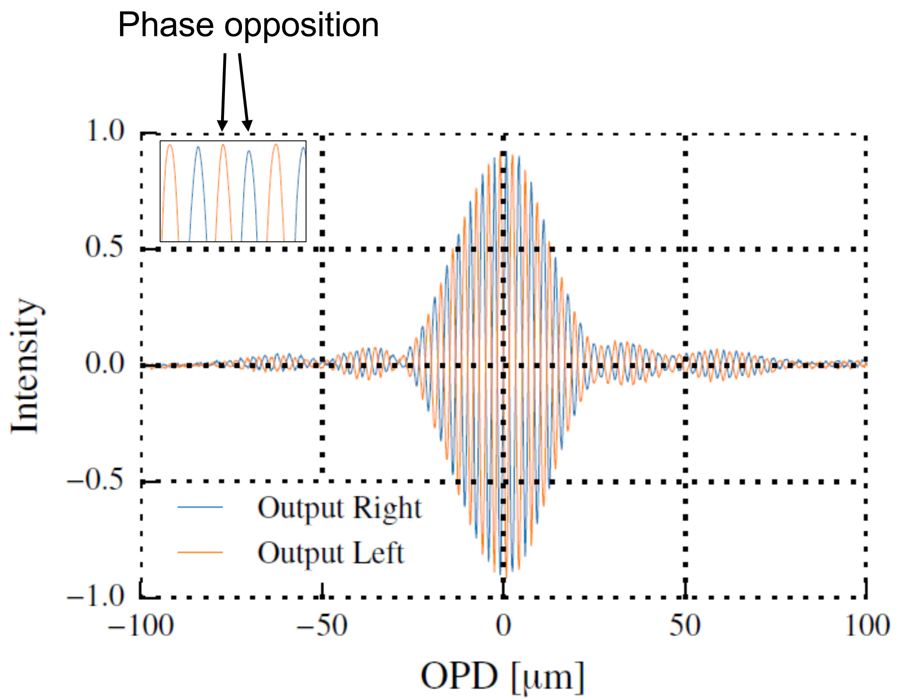


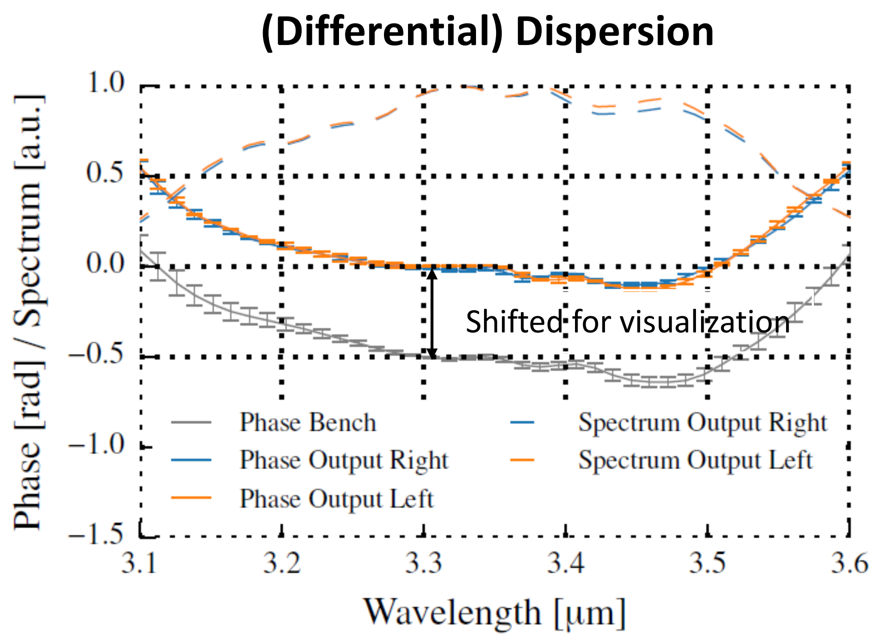
Measurement @ 3.39 µm



- ❑ Found excursion of max. ~10% from the to 50/50 ratio

Broadband interferogram (3.1-3.6µm, GLS)

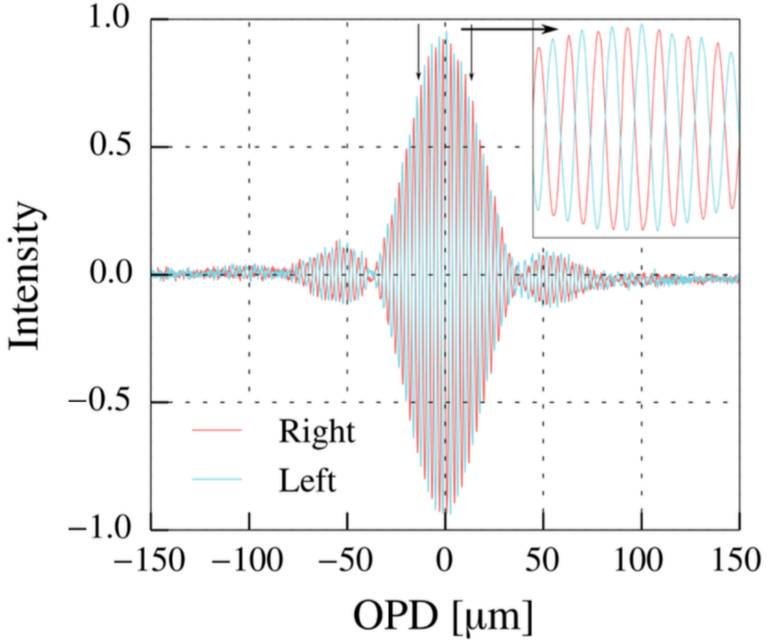


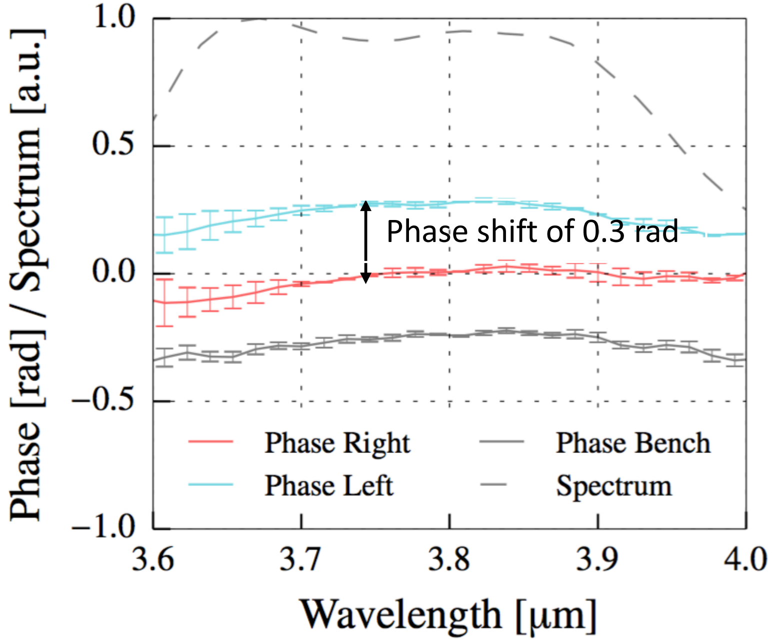


Broadband contrast in unpolarized light =**94.9%**

- π-phase shift due to energy conservation in the coupler
- Phase mainly corrupted by the experimental setup (probably pellicle beamsplitter)
- Variation of ca. **0.04 rad** across band after subtraction
- Coupler introduces almost no additional dispersion

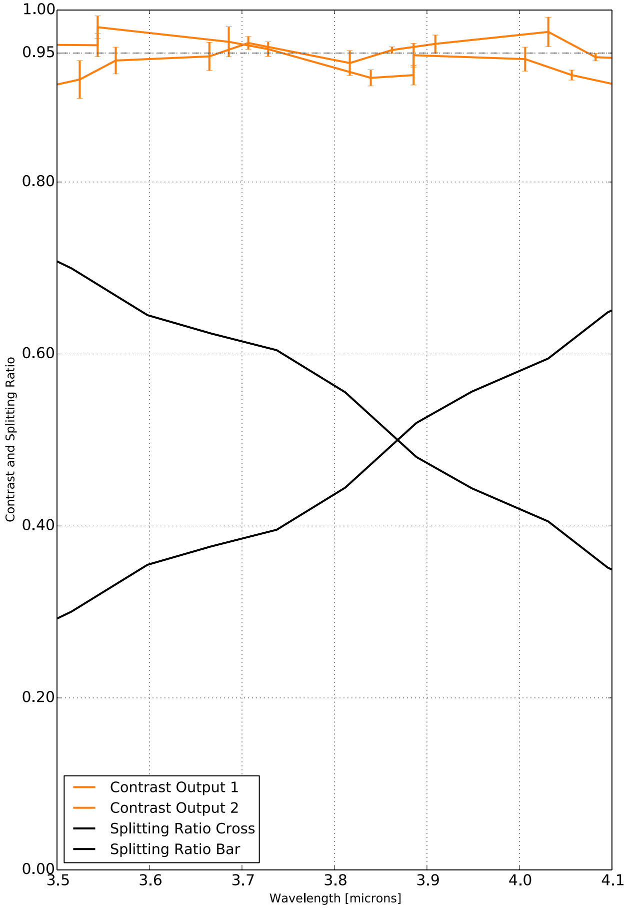
Broadband interferogram (3.6-4.0µm, ZBLAN)





Broadband contrast in unpolarized light =**93.8%**

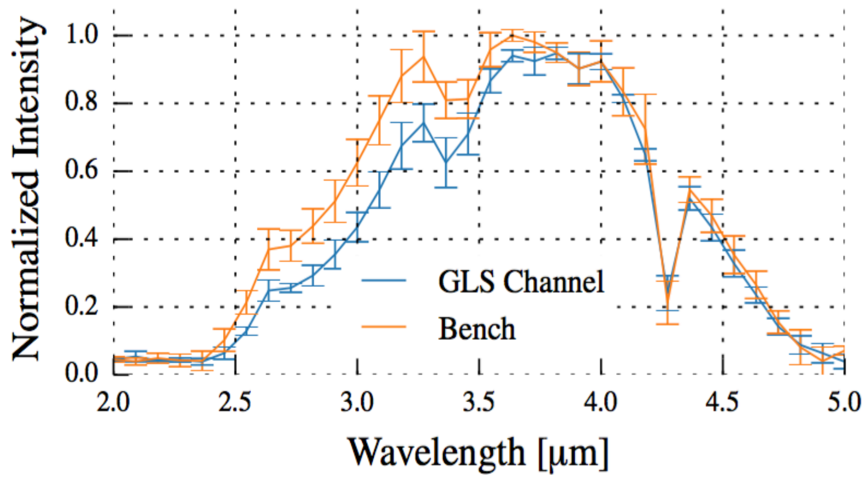
Disperse interferogram (3.6-4.0µm, GLS)



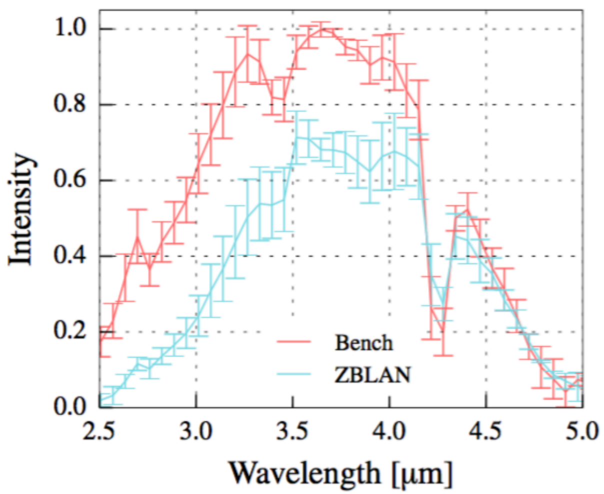
- ❑ Second GLS sample with crossing point around **3.8 µm**
- ❑ Direct measurement of the dispersed interferometric contrast
- ❑ Median instrumental contrast is **V~95%**
- ❑ The repeatability of the **coupling** (due to DL accuracy) seems to be an issue

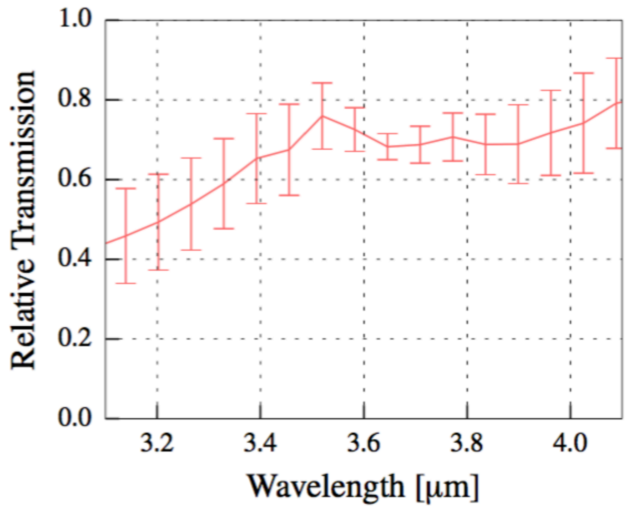
Transmission

GLS



ZBLAN





Coupler overall performance

Property	**3.39 µm**	**L band** (3.1-3.6)	**L' band** (3.6-4)	**M band** (4.5-4.9)
Integrated splitting ratio (all)	–	~50/50	~50/50	~50/50
Chromaticity splitting ratio	–	0.3–0.4/µm (GLS & ZBLAN)		
Differential birefringence	**~0.2 rad**	–	–	–
Phase variation (diff. dispersion)	–	<0.05 rad	<0.05 rad	<0.07 rad
Interferometric contrast	**98±0.5%**	**95±1%**	**94±1%**	**92±1%**
Modal behavior	SM	SM	SM	SM
Propagation losses(2)	–	**0.8 dB/cm**	**0.3 dB/cm**	–
Bend losses		**0.6 dB/bend**	**<0.05 dB/bend**	
Total throughput(3)		**26%(w/o RL 36%)**	**59%(w/o RL 62%)**	

orange = ZBLAN glass ; pink = GLS glass;

(1) Variance of the contrast limited by non simultaneous photometric correction
(2) Intrinsic + extrinsic (impurities) losses;
(3) Fresnel losses: GLS glass (~30%), ZBLAN (~7%)

Units for advanced functions

- **Asymmetric couplers**: non-identical interacting waveguides ($\beta_{wg1} \neq \beta_{wg2}$)
- **Tri-coupler** splitting devices
- **ABCD** beam combining unit: phase measurement

- Varying writing speed

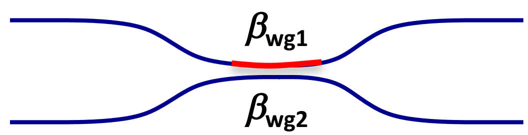
→ $\Delta n_{wg1} \neq \Delta n_{wg2}$

→ Wave sees effective indices β_{neff}

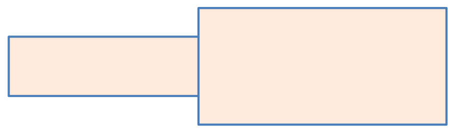
→ Phase shift

- Difficult to relate with high precision and repeatability writing parameters to Δn

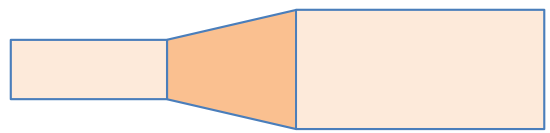
→ *Iterative try-and-error*



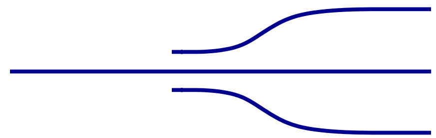
Asymmetric coupler



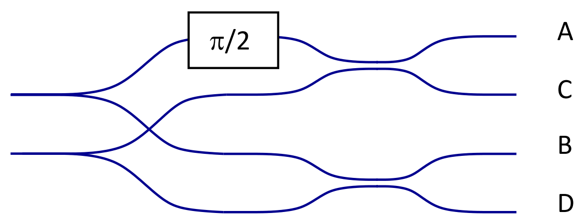
"Hard" transition



"Smooth" transition



Tricoupler



ABCD unit

Units for advanced functions

- **Asymmetric couplers**: non-identical interacting waveguides ($\beta_{wg1} \neq \beta_{wg2}$)
- **Tri-coupler** splitting devices
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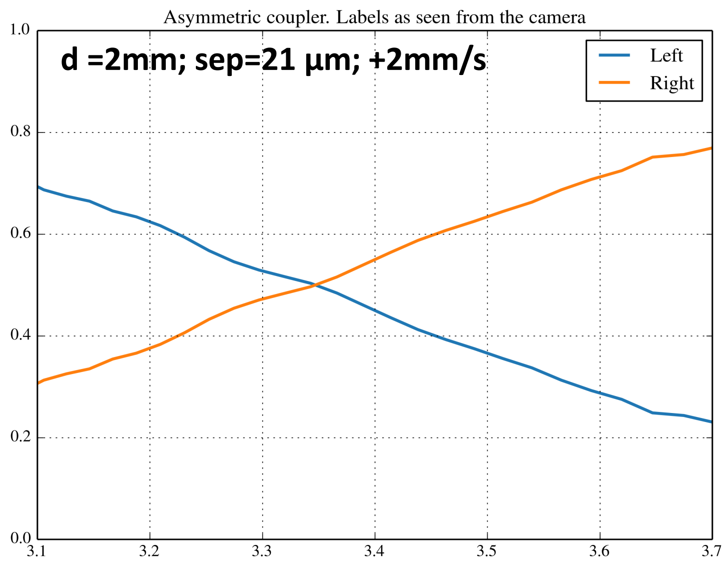
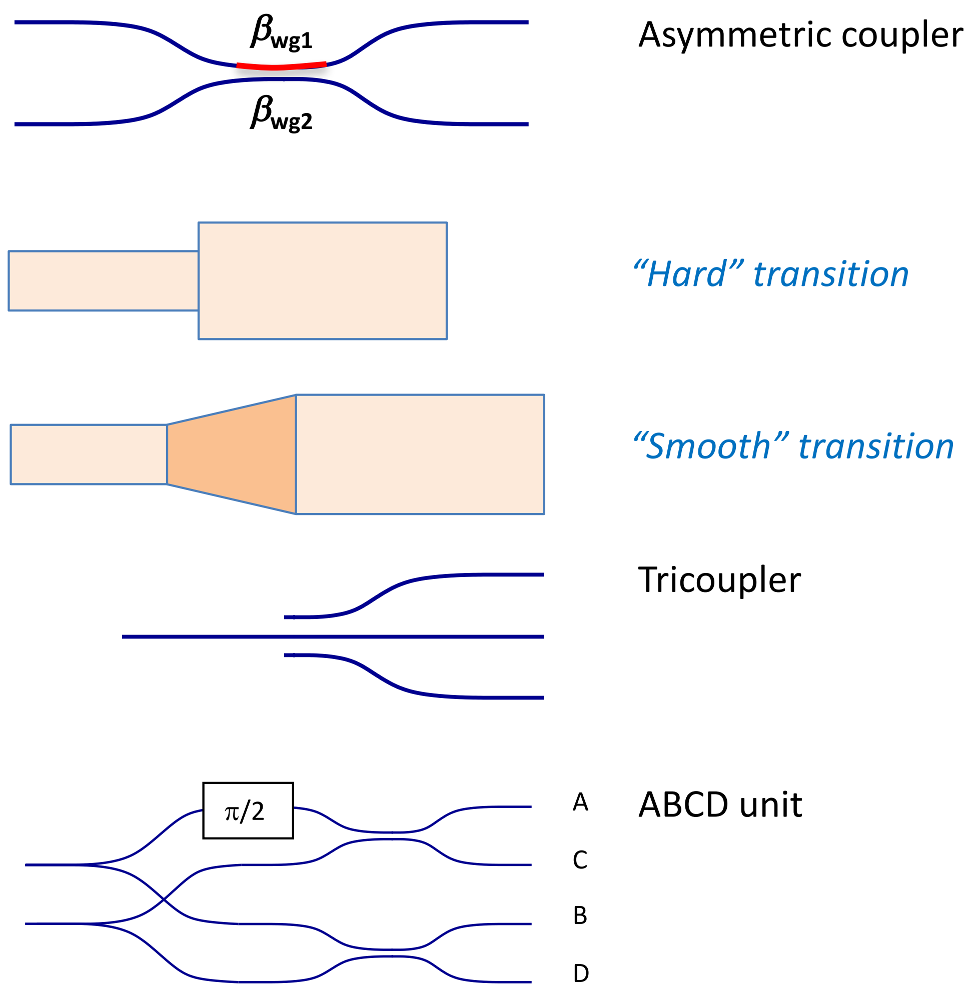
Asymmetric coupler





Units for advanced functions

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- **Tri-coupler** splitting devices
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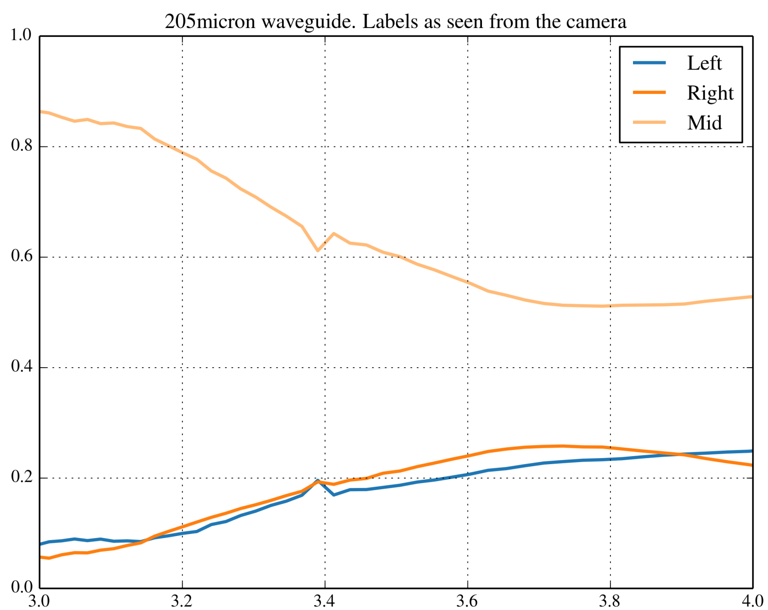
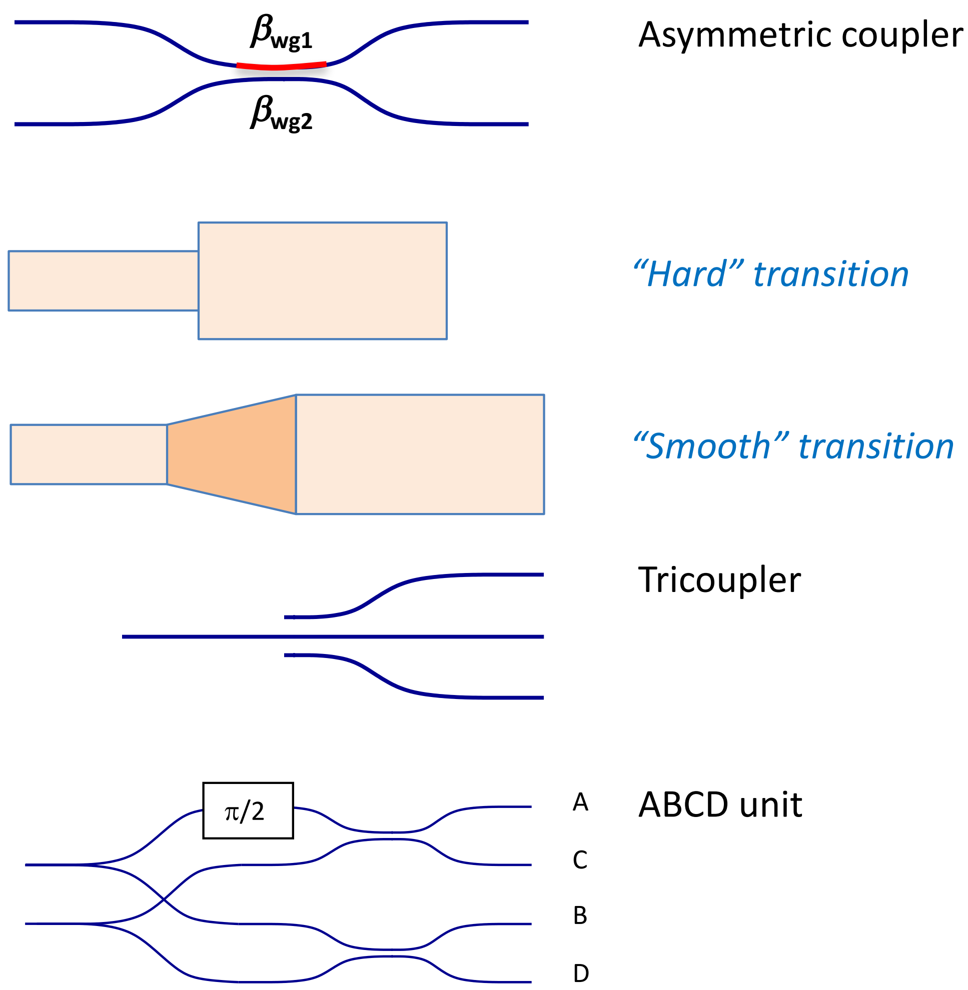
Tri-coupler





Units for advanced functions

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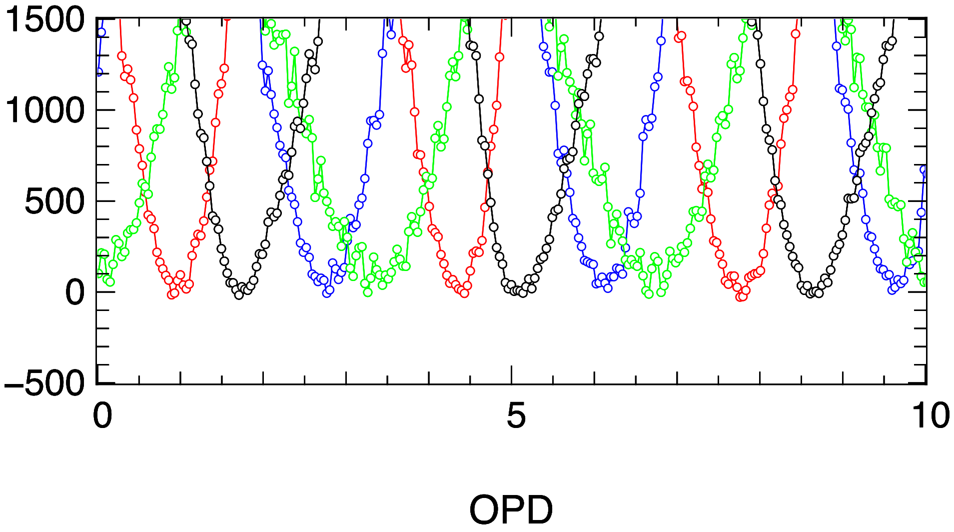
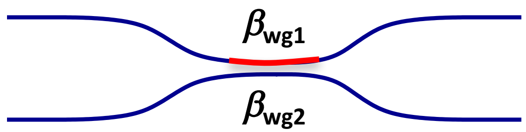
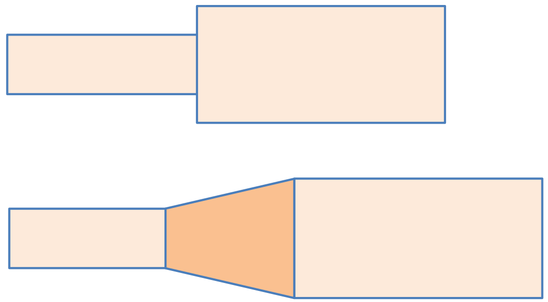
ABCD unit (monochromatic)

Speed: 1 mm/s -> 1.4 mm/s



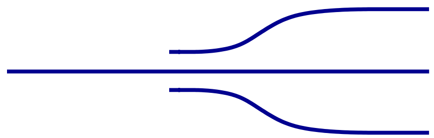


Asymmetric coupler

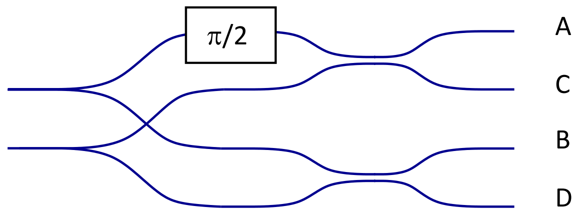


"Hard" transition

"Smooth" transition



Tricoupler



ABCD unit

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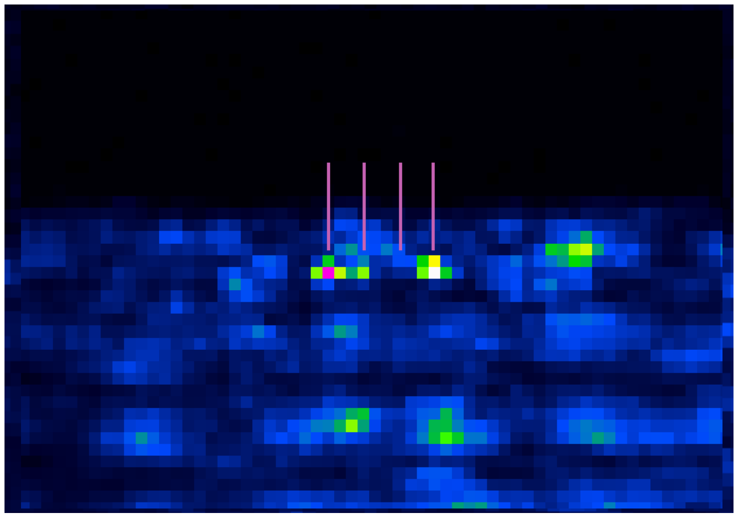
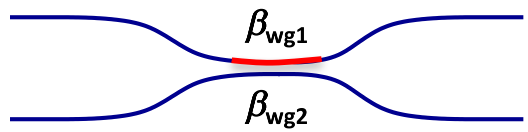
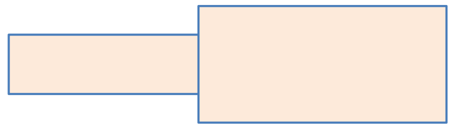
ABCD unit (monochromatic)





Asymmetric coupler



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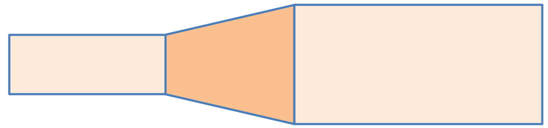
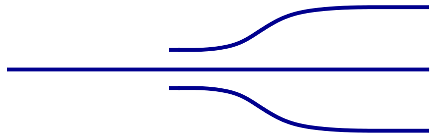
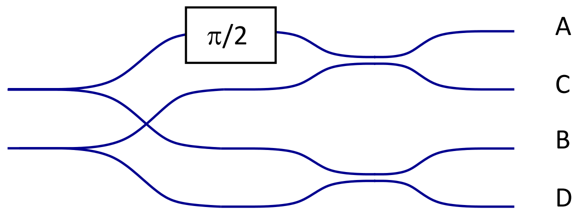


"Smooth" transition



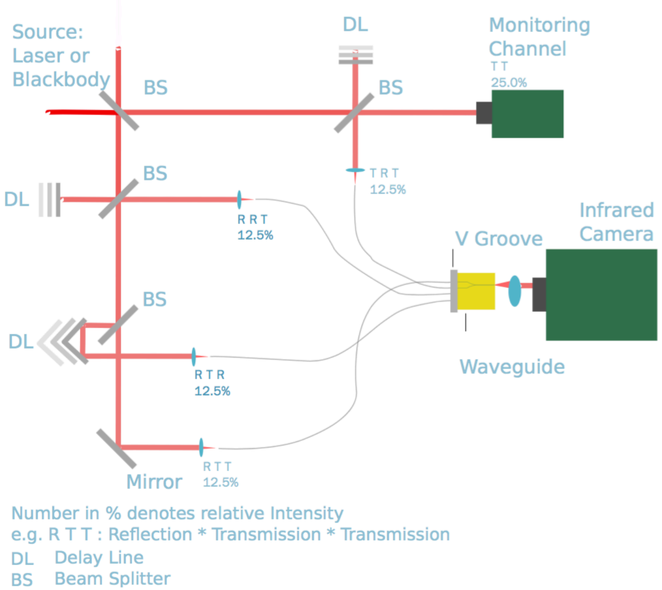
Tricoupler

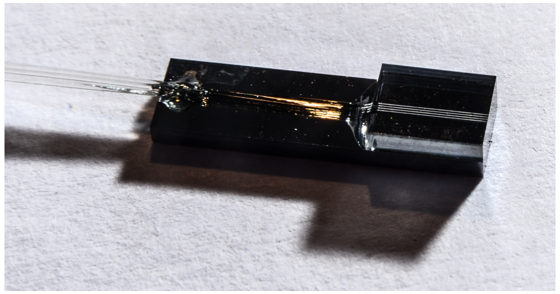


ABCD unit

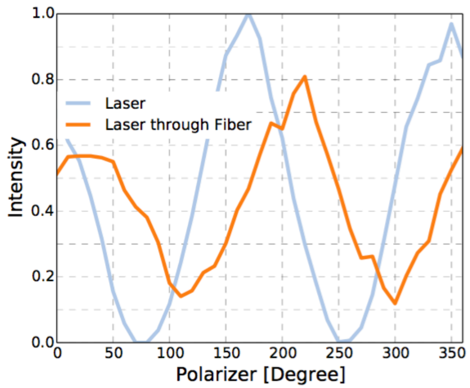
Example of future work/upgrade

- **3- or 4-Telescope breadboard**: custom or commercial **V-groove** and **supercontinuum** source
- Ideally using **polarization-maintaining** fibers (Verre Fluoré, University of Bath)
- Options at **study**: commercial step-index **fluoride** fibers (< 4.0-4.5 µm), **As_2S_3** SM fibers (3-5µm range)





(1) 125µm core-to-core
(2) Butt coupling (i.e. 2X Fresnel losses). Glue?



Conclusion and perspectives

- Shown advances in the development and detailed characterization of **3-5 µm single-mode integrated optics**
- **Quantitative results** shows promising IO solutions, provided further investigation

- Better understanding/mastering of the **repeatability** of laser writing
- Improve the balance "field confinement (i.e. Δn) / bends" and global **optimization** (e.g. mitigation of uncoupled background, implementing broadband SC source)
  - *Advancing the **development phase** within our current – and **future** - collaborations*
- Fiber-fed design (V-groove + polarization splitting), A/R coatings
- Continuation of our activity through the DFG-funded **NAIR project**: prototyping and on-sky demonstrator of astrophotonics devices for spectroscopy and interferometry (Collaboration Potsdam/Cologne/Heidelberg)