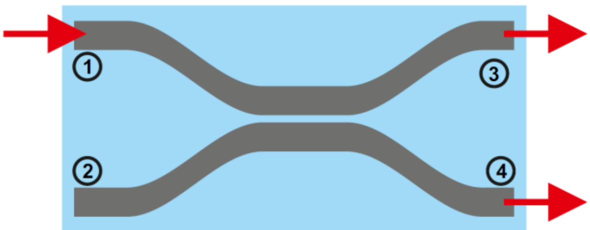
1 Directional coupler (2-3 Students)

Goal

The goal of this project is to make a 2 by 2 optical directional coupler with a defined power ratio for the two output branches. The directional coupler should be optimized for the operating wavelength of λ = 1550 nm. In a first directional coupler design, the output power should be equally split between the two arms (50/50) with minimal overall losses. In a second design, the output splitting ratio should be 90/10. The general geometry of a directional coupler is shown in Figure 1.

Tasks

1. **Literature search.** The first task is to familiarize with the theory behind directional coupling. This should give you an idea of the geometry that a directional coupler should have, and which parameters are critical to achieve the specified goals.
2. **Convergence**. Each model type should be tested for convergence with a small mesh study.
3. **Single mode waveguide.** The material of the core is Silicon Nitride or Silicon, while the cladding is SiO2.
    a. Simulate the out-of-plane cross-section and analyze the mode in the SiN or Si waveguide. For SiN, the technology used is 800nm thick stoichiometric SiN deposited with LPCVD (relevant for the refractive index). For Si, the waveguides will be based on 220 nm Silicon-on-insulator platform. Plot the effective index in respect to the waveguide width and determine the single mode cross-section.
    b. Using the 1D eigenmode solver of COMSOL (Boundary Mode Analysis), simulate the mode from in-plane perspective in 1D. Compare the result with the cross-section simulate and discuss a potential difference. If a difference is found, discuss possible reasons for this discrepancy.
4. **Bending losses**. Bending of the waveguide is required for the coupling section. The bending has to be optimized for the smallest radius with a minimal loss per bending. The structure can be symmetric, so only one bending radius optimization is needed.
    a. **NOTE: if you want, you could do asymmetric structure, but that would require 2 bend loss calculation. However, if you have an idea and good reason to do it, you are welcome to try!**
5. **Coupling section**. The entire structure should be modeled, and the coupling section should be optimized for the specified power ratios.
    a. **NOTE**: Sweeping the length of the coupling section and/or distance between the waveguides and plot the two output power can reveal the ideal coupling section parameters.
    b. **NOTE: There is a theoretical description of the directional coupler using coupled mode theory. Using the supermodes in the structure, analyze whether the theory matches the simulated result and discuss the result.** (Mandatory for group of 3)
6. **Wavelength**. Check how the coupling section behaves for different wavelengths from 1450-1650 nm.
7. **90/10 directional coupler**. After the wavelength test, the design should be adapted for the power ratio in the two arms to be 10%/90%. Again, this design will be checked for its coupling spectrum.
8. **Report and presentation.** The results of the project should be summarized in the form of a short report and 15 minutes presentation (10 minutes talk and 5 minutes for questions).



2 Ring Resonator (2-3 Students)

Goal

The goal of this project is to design and simulate a Silicon-on-Insulator optical ring resonator. The device should act as a notch filter at the operating wavelength of 1310 nm. In a second step, a cascaded multi ring resonators device has to be designed. In this configuration, rings with varying radii in series have to form an add/drop circuit with 60/40 power distribution. Fig. 2 shows an implementation example. The general geometry of an add/drop ring resonator and cascaded resonators are shown in Figure 1.

Milestones

1. **Literature search.** The first task is to familiarize with the theory behind ring resonators. The most important is to answer to questions of which parameters are playing the crucial roles. You should first calculate the ring parameters (radius) for the required resonance wavelength.
2. **Single Mode Waveguide.** Design a single mode Silicon or Silicon nitride waveguide (at λ = 1550 nm), using the 1D eigenmode solver of COMSOL (Boundary Mode Analysis). The material of the core is Silicon or silicon nitride, while the cladding is air.
3. **Ring Resonator.** Based on your calculation, the ring radius has to be optimized to have resonant behavior at 1550nm and minimal bending losses.
4. **Single Ring Filter.** The ring radius has to be further optimized not only to show resonance at 1550nm, but also have a Q factor and a FSR of about 10’000 and 10nm, respectively. Additionally, the coupling between the waveguide and ring resonator has to be such that the extinction ratio is above 20dB. Study how different geometric parameters change the resonance behavior of a single ring resonance. If two different materials have been tested, discuss the difference and the possible reasons.
5. **Cascaded Structure.** An add/drop filter design with cascaded ring resonators in series will be designed. The power distribution should be optimized to 60/40 at the two forward outputs.
6. **Report and presentation.** The results of the project should be summarized in the form of a short report and 15 minutes presentation (10 minutes talk and 5 minutes for questions).

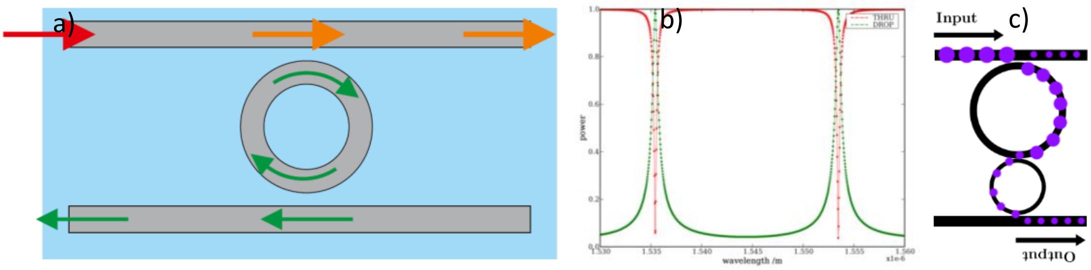


Figure 2: (a) The ring resonator structure is illustrated. (b) The expected transmission and reflection coefficients over a variation of the wavelength. (c) An illustration of two cascaded ring resonators.

3 Delay Interferometer (3 students)

Goal

The goal of this project is to design and simulate a delay interferometer based on a Mach-Zehnder configuration for the purpose of verifying the coherence of a light source. This project can be divided into two main parts. One is the design and optimization of the coupling section, which is the splitting and interference section of the interferometer. Second, an asymmetric delay line should be designed and optimized to induce a π-shift in one arm of the interferometer. Both designs should have minimal losses and be optimized for the operating wavelength of 1550nm. The general geometry of a Mach-Zehnder interferometer is shown in Figure 3.

Task

Milestones

1. **Literature search.** The first task is to familiarize with the theory behind Delay Interferometers, especially the Mach-Zehnder configuration. Important is also the theory about directional coupling. You can use theory to calculate the delay line length to achieve a specific relative phase shift.
2. **Single mode waveguide.** Next is to design a single mode Silicon waveguide (at λ = 1550 nm), using the 1D eigenmode solver of COMSOL (Boundary Mode Analysis). The material of the core is Silicon, while the cladding is air. In both, the coupling scheme and the delay line, the waveguide dimension should be the constant.
3. **Splitting scheme.** A splitting scheme based on a directional coupler should be implemented with a splitting ratio of 50/50. The coupling length can be reduced by optimizing the waveguide separation. This reduces the overall dimension of the device. Similarly, the bending curvature should be optimized for low bending with minimum losses.
4. **Interference scheme.** For the coupling (interference), two options are possible. First option, you can use the same scheme as used for your splitting scheme. Based on the interference, the power will be split between the two outputs. Second option, you design a multi-mode interferometer (MMI), such as to observe interference behavior on a single output (a bit more effort, but you can collaborate with the MMI group).
5. **Symmetric interferometers**. In a first step, design and optimize the delay line with symmetric dimension. This step is useful to optimize the bending radius of the two arms. Note that, this should result in a constructive interference at the output.
6. **Asymmetric Delay line.** Based on your calculation, optimized the delay line length for a π-shift (wavelength of 1550nm). Do not forget the additional phase delay in the reference line!
7. **Putting the things together**. In the last step, the entire structure has to be assembled, and the π-shift should be verified by calculating the extinction ratio on the output lines (> 10dB). If possible, make a sweep of the delay line. With this, you can plot the output power as a function of the relative phase shift.
8. **Convergence**. The final structure should be tested for the mesh size.
9. **Report and presentation.** The results of the project should be summarized in the form of a short report and 15 minutes presentation (10 minutes talk and 5 minutes for questions).

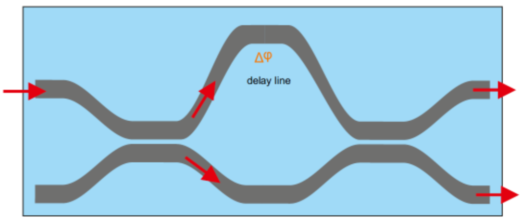


Figure 3: A Mach-Zehnder interferometer configuration is shown.

4 Bragg Mirror (2-3 students)

Goal

Goal of this project is to design a Bragg mirror with specified reflectivity R > 90% at the operating wavelength of λ = 1550 nm. In the first design, only one wavelength will be considered. In the second run, a parametric sweep of wavelengths will be performed, so that 3dB (half of the power) reflectivity can be achieved over a range of wavelengths. Figure 4 illustrates a general geometry of a Bragg reflector.

Milestones

1. **Literature search.** The first milestone is to familiarize with the theory behind the Bragg mirror. The most important is to answer to questions which parameters are playing the crucial role.
2. **Single mode waveguide (COMSOL).** The following milestone is to design a single mode Silicon Nitride waveguide (at λ = 1550 nm), using the eigenmode solver of COMSOL. The material of the core is Silicon Nitride, while the cladding is SiO_2. The technology used is 800nm thick stoichiometric SiN deposited with LPCVD (relevant for the refractive index)
3. **Infinite Bragg mirror.** The next milestone is to perform theoretical calculations of the infinite Bragg mirror (2 physical dimensions are infinite), so the starting design points (number of periods, filling factor and period) for COMSOL simulations could be chosen (see Figure).
4. **COMSOL simulation of the mirror.** Once the initial parameters are known, the Bragg mirror should be simulated in COMSOL with the following goals:
    a. **Reflection coefficient > 90% for** $\lambda_c = 1550$ nm
    b. **Reflection coefficient > 3dB for** $\lambda_c \pm 100$ nm
5. **Convergence test.** To make sure that results are realistic, you should simulate for different mesh sizes.
6. **Report and presentation.** The results of the project will be presented in the form of a short report and 15 minutes presentation (10 minutes talk and 5 minutes for questions).

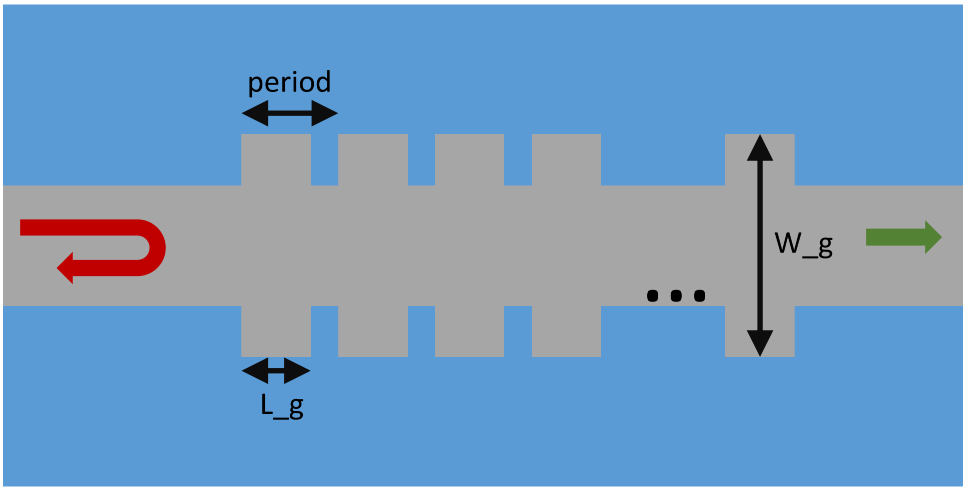


Figure 4: The Bragg mirror. The most important design parameters are the period, filling factor (L_g/period) and the thickness of the Si grating part (w_g). Number of periods N will determine the sharpness and strength of the mirror.

5 Multimode Interferometer (2-3 Students)

Goal

Goal of this project is to design a multi-mode interferometer (MMI) with specified output coupling operating at the wavelength of λ = 1550 nm. In the first design, a 1x2 configuration is considered with an output ratio of 50:50. In the second run, the MMI should be optimized for an output ratio of 10:90. The general geometry of a MMI is shown in Figure 5.

Task

1. **Literature search.** The first task is to familiarize with the theory behind the MMI. The most important is to answer to questions which parameters are playing the crucial role. Based on the theory you can estimate initial parameters.
2. **Single mode waveguide (COMSOL).** The following task is to design a single mode Silicon Nitride waveguide, using the 1D eigenmode solver of COMSOL (Boundary Mode Analysis). The material of the core is Silicon Nitride, while the cladding is SiO_2. The technology used is 800nm thick stoichiometric SiN deposited with LPCVD (relevant for the refractive index)
3. **MMI.** Based on the estimated dimensions, you can design and simulate the MMI. From this point you can optimize the structure for a 50/50 coupling ratio. Make sure the overall losses are be below 1dB and minimize the reflections.
    a. **Note.** You can start by simulating a long interference section, and optimize only the width of the MMI. This allows you to then clearly see the 50/50 and 90/10 interference lengths.
    b. **Note.** You can use tapers to reduce scattering losses and reflection.
    c. **Note.** The placement of the input/output waveguides can be different for different ratios.
4. **Convergence test.** The results should be tested for different mesh sizes.
5. **Second MMI.** The 1x2 MMI should be optimized for the new goal:
    a. **Output ratio of 10:90 for** $\lambda_c = 1550$ nm
    b. **Overall losses below 1dB**
6. **Report and presentation.** The results of the project should be summarized in the form of a short report and 15 minutes presentation (10 minutes talk and 5 minutes for questions).

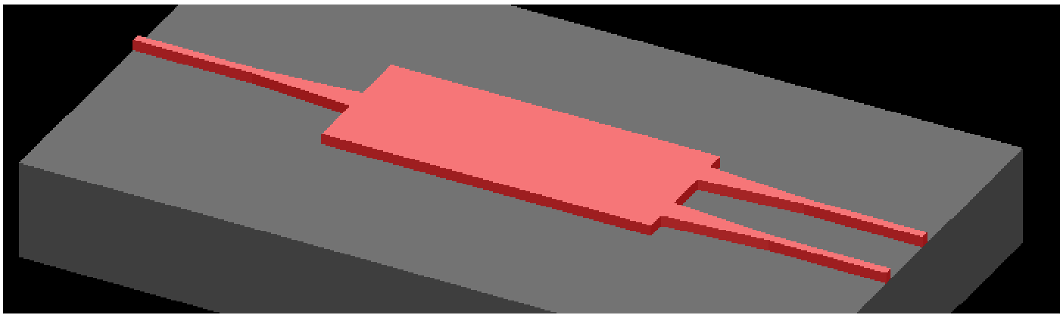


Figure 5: Multimode interferometer 1x2 configuration.

6 Grating Coupler (3 Students)

Goal

One of the methods to extract the light from an optical chip is to use grating coupling for coupling into a fiber out-of-plane Goal of this project is to design a the grating coupler in such a way, that the Bragg condition is fulfilled to diffract the light toward the fiber. There are mainly three parameters of interest in the grating coupler itself. In order to reduce the complexity, simulate the grating for a 10° standard single-mode fiber. Base your simulation on standard Silicon-on-Insulator technology with a 3 um Buried Oxide layer (BOX). Important: the silicon substrate needs to be included in the simulation as reflection between the BOX and substrate changes the coupling efficiency. The general geometry of such a coupling structure is shown in Figure 1.

Task

1. **Literature search.** The first task is to familiarize with the theory behind the grating couplers. The most important is to answer to questions which parameters are playing the crucial role. Based on the theory you can estimate initial parameters.
2. **Single mode waveguide.** The input waveguide geometry is specified as in the figure. The following task is to check how many modes are supported by the waveguide, using the 1D eigenmode solver of COMSOL (Boundary Mode Analysis).
3. **Effective Index with varying etch depth.** The grating equation can be simplified with the effective index dependent on the etch depth. In a first step simulate the effective index with varying etch depth and afterward implement the Bragg condition for the parameters of the grating coupler.
    a. **Note.** There is some great literature showing the design process of a simple grating structure.
    b. **Note.** The fiber can be modelled simply by a core and a cladding rectangle. Make sure that the angle is correct and that the position of the fiber is optimal. For an optimal position, you can check the diffracted field and position the fiber such that the middle of the core is at the maximum. For finer tuning, a short fiber position sweep can be done. For the same angle, the position of the fiber should be similar in respect to the start of the grating coupler.
4. **Convergence test.** The results should be tested for different mesh sizes.
5. **Optimization:** After implementing the grating equation (Bragg condition or Phase matching), find the optimum fill factor for an etch depth of 100 nm, 70 nm and 50 nm. Optimal coupling efficiency (CE) can be as low as 1.5 dB. Find a grating with CE < 3 dB (S21 > -3 dB) and S11 < -20 dB.
6. **Wavelength**. Check how the coupling section behaves for different wavelengths from 1450-1650 nm.
7. **Specifications**
    a. Fiber: $core\ diameter = 8\ \mu m,\ n_{core} = 1.44,\ n_{clad} = 1.43,$
    b. Wavguide: thickness = 220 nm, $n_{core} = 3.47,\ n_{clad} = 1.44,$
8. **Report and presentation.** The results of the project should be summarized in the form of a short report and 15 minutes presentation (10 minutes talk and 5 minutes for questions).

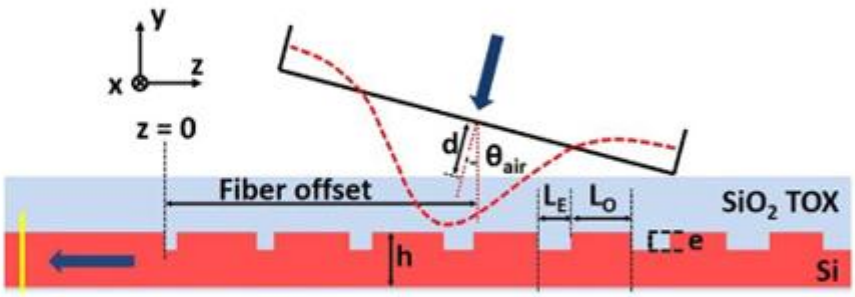


Figure 6: Grating Coupler (side view). Figure from Riccardo Marchetti et al., "High-efficiency grating-couplers: demonstration of a new design strategy". Nature 2017.

7 Waveguide Crossings (2-3 Students)

Goal

The goal of this project is to design a waveguide crossing with minimal transmission losses operating at the wavelength of λ = 1550 nm. In the first design, shown in Figure 8.a), a 2 (1x1) WG crossing configuration is considered with maximal transmission into the straight waveguide. Additionally, a 2x2 WG crossing configuration can be evaluated for maximal transmission and minimal crosstalk.

Task

1. **Literature search.** The first task is to familiarize with state-of-the-art waveguide crossings and the theory behind it. Based on the theory you can estimate initial parameters.
2. **Single mode waveguide (COMSOL).** The following task is to design a single mode Silicon waveguide (at λ = 1550 nm), using the 1D eigenmode solver of COMSOL (Boundary Mode Analysis). The material of the core is Silicon Nitride, while the cladding is Silicon Dioxide.
3. **Simple crossing.** As a reference, a simple straight crossing is simulated.
   a. **Note.** Make use of symmetries when building the model.
4. **Expanding crossing.** Based on the estimated dimensions, you can design and simulate the crossing with mode expanders. From this point you can optimize the structure for a maximal S21 transmission. Make sure the overall losses are below 0.3 dB and minimize the reflections.
   a. **Note.** Try to minimize the free parameters of the mode expanders for a more simple design and sweeping.
5. **Convergence test.** The results should be tested for different mesh sizes to make sure that the mesh is fine enough in order to get accurate results.
6. **Wavelength test.** Check for the optical bandwidth of your crossing.
7. **2x2 WG crossing.** Include additional waveguides without mode-expanders at the appropriate positions to maximize the through transmission while keeping a compact design.
8. **Report and presentation.** The results of the project should be summarized in the form of a short report and a 15 minutes presentation (10 minutes talk and 5 minutes for questions).

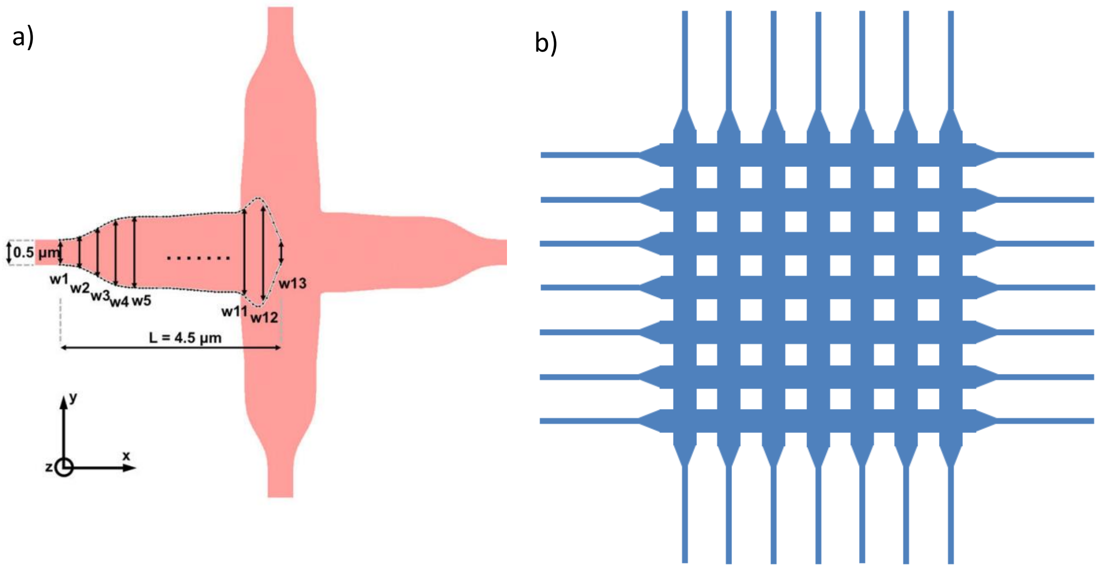


Figure 7: (a) A 2 waveguide crossing with mode expanders is shown (Ma, Yangjin, et al. "Ultralow loss single layer submicron silicon waveguide crossing for SOI optical interconnect." Optics express 21.24 (2013): 29374-29382). (b) A Network of a 7x7 WG crossing is illustrated (Zhang, Yang, et al. "Ultralow-loss silicon waveguide crossing using Bloch modes in index-engineered cascaded multimode-interference couplers." Optics letters 38.18 (2013): 3608-3611).

8 Optical Metamaterial

Goal

For this task the goal is to design metamaterial perfect absorbers based on a metal- insulator- metal stack. Metamaterials can be designed with various designs and for different wavelengths. Here, two metamaterials should be designed in such a way that both achieve near unity absorption at a wavelength of λ = 2700 nm. One of the metamaterials should exhibit a broadband absorption and the other a narrow band absorption peak.

Tasks

1. **Literature search.** The first task is to familiarize with state-of-the-art metamaterials and the underlying concepts.
2. **Narrow band metamaterial.** In this step a metamaterial should be designed such that it exhibits a narrow absorption peak at a wavelength of λ = 2700 nm. This can be achieved by selecting a suited metamaterial geometry and sweeping the geometric parameters.
3. **Parameter study.** Analyze how the different parameters of the metamaterial influence the absorption spectra with respect to peak position and FWHM.
4. **Polarization Angle.** Analyze how strong the absorption of the metamaterial depends on the angle polarization of the incoming light.
5. **Broad band metamaterial.** Repeat steps 1- 5 but realize a broadband absorbing metamaterial.
6. **Active material.** Cover one of the metamaterial structures with a suitable light absorbing material and investigate how much light is absorbed in the material with and without the metamaterial.

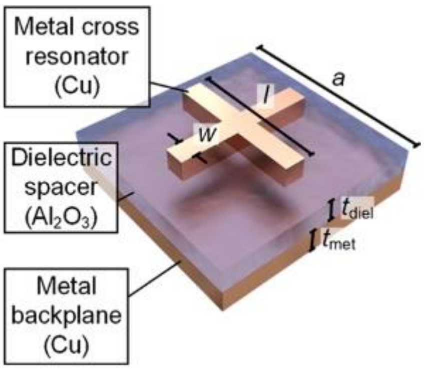


Figure 8: Compact Mid-Infrared Gas Sensor. (Lochbaum, Alexander, et al. "Compact Mid-Infrared Gas Sensing Enabled by an All-Metamaterial Design" NanoLetters (2020): 4169-4176).

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