

iBEAM: substrate-integrated hollow waveguides for efficient laser beam combining

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Abstract: Laser light sources are routinely applied building blocks in optical sensor technologies. While lasers are emitting at a precisely defined wavelength within narrow emission bands, chem/bio-sensing applications frequently demand multi-wavelength illumination for addressing a series of species. Instead of using broadband radiation sources, it is a viable strategy to efficiently combine the beams emitted from different lasers to maintain the spectral brightness and yet cover extended wavelength regimes. In this study, substrate-integrated hollow waveguides (iHWGs) are reported as a versatile and efficient alternative compared to conventional beam combining concepts, especially for applications in the mid-infrared spectral regime leading to a highly efficient multi-port beam combiner—the iBEAM.

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1. Introduction

Beam combining technologies are of increasing interest for a wide range of applications ranging from medical diagnostics, communications technologies and remote sensing tasks to industrial manufacturing, astronomy and spectroscopy systems [1,2]. Frequently, free space optical beam combining based on gratings [3], prisms [4], tilted alignment, volume Bragg gratings, fibers or dichroic mirrors [5–8] provide only narrow bandwidths and are mostly limited by the transmission windows of the utilized optical building block. Providing integrated solutions is particularly interesting for integrated photonic circuit platforms. Ultrabroadband on-chip beam combining concepts have been demonstrated for the combination of wavelength bands ranging from 350 nm to 1.5 µm and from 1.5 µm to 6.5 µm based on silicon and silicon nitride waveguides [9]. However, such on-chip solutions require either tailored light sources that can be integrated with waveguides on a photonic chip [10] or highly sophisticated coupling motives to efficiently feed light into the on-chip optics. These concepts usually result in low emission power of the integrated laser sources or high coupling losses. Furthermore, silicon or silicon dioxide based on-chip photonics are optimized for telecom wavelengths around 1.5 µm [1] and have limited transparency for longer wavelengths until becoming completely opaque $\sim 4 \,\mu m$ due to silicon oxide absorption. However, by removing silicon oxide from the silicon waveguide structures allows the expansion of the transparent window of silicon on-chip waveguide of up to 8.5 μ m [11]. Transmission limitations resulting from absorption bands of dielectric waveguide materials can be superseded by substrate integrated hollow waveguides (iHWG), that rely on reflective metal sidewalls. Most metals show a high reflectivity towards the longer wavelength regime whereas dielectrics are limited

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to selected materials such as diamond, chalcogenides, silver halides (AgCl_xBr_{1-x}, AgX), germanium (Ge) or gallium arsenide (GaAs), which are readily used for mid-infrared waveguides or as optical transducer elements in attenuated total reflection (ATR) chem/bio sensing schemes [12]. The mid-infrared (MIR) however is particularly interesting for chem/bio sensing scenarios, since well pronounced transitions of virtually any organic and inorganic analyte substances may be accessed within this spectral window [13]. Using interband cascade lasers (ICLs) and quantum cascade lasers (QCL) [14] tailored and/or tuned to specific wavelengths in this regime, MIR laser spectroscopy has gained increased interest in recent years. iHWGs have been developed as a miniaturized and robust alternative to elongated hollow core fibers [15,16] and are readily fabricated via computerized numerical control (CNC) assisted milling processes. They can be uniquely tailored in overall size, substrate material, surface coating and internal waveguide structure/geometry/dimensions to meet application-specific demands. In this context, small-footprint devices have been developed [17] mainly for Fourier transform infrared (FTIR) and MIR laser based [18–20] chem/bio sensors for example exhaled breath analysis [21,22], the determination of environmental pollutants [23–25] and in catalysis research [26,27]. Recently, gas phase sensing in the near-infrared (NIR) regime utilizing iHWGs has been demonstrated for the detection of short n-Alkanes (n = 1-4) by guiding NIR radiation from about 909 nm to 2170 nm within an iHWG channel that simultaneously served as a miniaturized gas cell [28,29]. The level of integration, robust structure, design freedom and wide spectral reflectivity provide iHWGs with an ideal technology platform for broad bandwidth beam-combining in laser-based applications, especially in the MIR spectral region. The iHWG-BEAM design reported in this study (iBEAM) is based on CNC-milled aluminum which efficiently reflects MIR wavelengths, provides a low-cost substrate material and high flexibility. Furthermore, the iBEAM is designed and optimized design parameters are derived for fiber interfacing using AgX fibers, which facilitates efficient radiation coupling from bulk laser heads to the iBEAM entrance facets. The developed beam combiner structures have been characterized with respect to propagation performance, bending losses and spectral beam-combining features.

2. Design and fabrication

The iHWGs used in this study are based on a structured aluminum substrate. Edge lengths of the final iBEAM of 5 cm and an overall height of 2 cm were selected to facilitate integration of the iBEAM building block into optical systems. In addition, with this thickness the aluminum substrate was sufficiently robust to prevent potential warping during the machining process. The internal hollow channel dimensions were selected at 2 mm depth and 2.1 mm width. Therefore, the milling head was guided twice through each channel, which resulted in a mirror-like surface finish with a RMS surface roughness of < 100 nm. A more detailed description of the milling process is given elsewhere [15]. The out-coupling port was equipped with a polished aluminum funnel matching the 2 x 2.1 mm waveguide channel to an AgX fiber core diameter of 800 µm. Furthermore, all radiation input/output ports of the iBEAM were equipped with a fiber sub miniature A (F-SMA) screw mount facilitating direct coupling with F-SMA terminated AgX fibers (NA = 0.3). As a result, the outer design of the iBEAM is based on constraints given by machining technologies and matching standard fiber coupling interfaces. The waveguide channel design originates from matching F-SMA interfaces with anchor points for designing iBEAM devices with optimized propagation performance based on this reported prototype device. Individual waveguide channels are merged into a single output port, and the individual beams are combined via reflections at the inner walls of the hollow waveguide core channel. Figure 1(a) illustrates the internal waveguide channel layout and the port labeling that was used. A typical fiber attachment is shown in Fig. 1(b) with 5 in-coupling ports and the out-coupling port connected to F-SMA terminated AgX fibers as well as two capped connections. Losses per port, as derived during



the subsequently described routines are shown in Fig. 1(c) and a typical 3D laser confocal microscopic image of the internal waveguide surface is shown in Fig. 1(d).



Fig. 1. a) Internal channel layout and port assignment of a typical iBEAM beam combiner. b) iBEAM fiber coupled with two blind/capped ports. c) Typical basic losses per port of a 7-port iBEAM without correction for in coupling losses, bending losses or transmission losses at a wavelength of 5.8 μ m (1720 cm⁻¹). d) 3D laser confocal image of an internal hollow waveguide surface.

3. Transmission characteristics

The surface roughness of the internal waveguide sidewalls was determined via a 3D laser confocal microscope (Fig. 1(d)). A RMS roughness value of < 100 nm was achieved without any additional post-processing after the milling step and is ideally suited for guiding infrared radiation in the 3-12 µm spectral regime. The transmission performance and bending losses were evaluated using a Daylight Solutions MIRcat QCL operated in continuous-wave (cw) mode and kept at a constant temperature of 18 °C and a Gentec-EO power meter. The QCL emits a TEM_{00} spatial mode and is >100:1 vertically linear polarized. The laser was tuned from 5.3 to 6 μ m at 0.1 μ m increments and then to 10.6 μ m (943 cm⁻¹), with typical wavelengths of 5.8 μ m (1720 cm⁻¹) and 10.6 μ m (943 cm⁻¹) representing the emitted center wavelength of the individual QCLs. The MIRcat QCL provided collimated radiation which was focused via a zinc selenide (ZnSe) lens onto the end-facet of an AgX fiber that was coupled to the respective port of the iBEAM. The overall losses per port of a 7-port iBEAM device are illustrated in Fig. 1(c). Losses increase from the shortest pathlength port 1 for extended waveguide channels and narrower bends for port 2, 3, 5, 6 and 7. Furthermore, losses of mirrored geometrical layouts are virtually the same for pairs of ports 1 and 7, 2 and 6 as well as for ports 3 and 5. For determining the propagation losses for straight channel transmission, iHWGs of different lengths (2, 3, 4, 5, 7.5 and 8.5 cm) were fabricated according to the targeted design of the final iBEAM. Transmission losses for propagation along a straight channel were determined in the range of 0.6(2) dB/cm at 5.8 μ m (1720 cm⁻¹) and 1.5(4) dB/cm at 10.6 µm (943 cm⁻¹) (Fig. 2(a)). Slightly elevated propagation losses



towards 10.6 μ m are due to a strong absorption feature of aluminum oxide (Al₂O₃), which is centered at a wavelength of ~12.5 μ m (800 cm⁻¹). The loss behavior follows a relation



Fig. 2. a) Propagation losses of an aluminum-based iBEAM depended on wavelength and waveguide length. b) Transmission loss corrected bending losses of an aluminum based iBEAM at a wavelength of 5.8 μ m (1720 cm⁻¹). c) Exemplary R/R₀ IRRAS spectra of the interior aluminum surface at 13°, 50° and 80° beam incidence. d) Relative reflectance at a wavelength of 10 μ m (1000 cm⁻¹) of polished aluminum surfaces for angles of incidence ranging from 10° to 83°.

according to loss (dB) = $-8.3 + 0.6 \cdot (Waveguide Length (cm))/cm + 1.4 \cdot (Wavelength (cm))/cm + 1.4 \cdot$ $(\mu m)/\mu m$ for short propagation lengths between 2 cm and 8.5 cm and for a wavelength in the range 5.3-6 µm. For determining bending loses, various bending radii were evaluated within the constraints of the targeted iBEAM layout. Bending losses were derived to follow loss $(dB) = 10.934*(bend radius)^{-0.863}$ at 5.8 µm (1720 cm⁻¹) (Fig. 2(b)). A slope of the bending radii function below 1/e facilitates low bending losses. With bending radii > 5.7 cm, low bending losses are achieved for the reported hollow waveguide channels while maintaining a compact device layout. Coupling losses from fibers to hollow waveguide channels were determined at 6.4(9) dB. For a typical iBEAM device, the combined losses sum up to \sim 12 dB for each port. In addition to the evaluation of the bulk transmission properties of the iBEAM, single bounce reflectivity of the internal aluminum sidewalls was evaluated for a typical specimen with a Bruker Vertex 70 spectrometer equipped with an infrared absorption reflection (IRRAS) module and compared to an ideal gold mirror with unpolarized radiation within a spectral window ranging of 2.5-25 μ m (4000 to 400 cm⁻¹). Typical IRRAS spectra for 13° , 50° and 80° angles of incidence are shown in Fig. 2(c). The spectra are superimposed with absorption bands of atmospheric carbon dioxide (CO₂) and water (H₂O) and an ice band at \sim 3500 cm⁻¹ due to frozen water using a liquid nitrogen cooled mercury-cadmium-telluride (MCT) detector. For steep angles of incidence, a relative reflectivity in comparison to a gold mirror of close to 1 is achieved. Towards shallower angles of incidence, a relative reflectivity of about 0.9 is still maintained. Notably, the characteristic absorption aluminum oxide (Al₂O₃), which is centered at a wavelength of ~12.5 μ m (800 cm⁻¹) becomes more prominent

when approaching grazing incidence angle. As shown in Fig. 2(c), the relative reflectivity at 10 μ m (1000 cm⁻¹) is close to 1 for angles of incidence of up to 78°. Consequently, IR radiation is ideally propagated within a hollow waveguide for angles of incidence that remain < 78°, which corresponds to smaller numerical apertures (NA) as provided by the coupling fibers. On the other hand, rays at steeper incidence angles are reflected multiple times, i.e. more often than rays at shallower angles of incidence, which are however reflected more effectively. Hence, a certain averaging effect between rays within the center beam and peripheral rays can be anticipated and will be investigated in more detail in further studies.

4. Beam combining performance

Broadband transmission properties of an iBEAM were evaluated with a Bruker Alpha FT-IR spectrometer within a spectral range of 7500-350 cm⁻¹ (1.3-28.6 μ m) at a spectral resolution of 2 cm⁻¹. Single-channel MIR transmission of the iBEAM resembles closely the black body radiation characteristics of the MIR source in the FT-IR and corresponds to the reflection properties derived via IRRAS. The beam combing performance of the iBEAM structure was evaluated using using three laser systems coupled into the device: two Daylight Solutions MIRcat QCL systems and s single Daylight Solutions EC-QCL 21062 TLS operated in a pulsed mode at a constant temperature of 18 °C. Each laser head was fiber-coupled to the iBEAM and the combined radiation emitted from the output port of the iBEAM, was evaluated using a Bruker Vertex 70 spectrometer with a spectral resolution of 0.5 cm⁻¹. Radiation from the three laser sources combined via the iBEAM is shown in Fig. 3(b) for the QCLs tuned to narrowly spaced wavelengths, i.e. 1800, 1700, 1600 cm^{-1} (5.6, 5.9 and 6.25 μ m) and then tuned to widely spaced wavelengths, i.e. 1700, 1568 and 943 cm⁻¹ (5.9, 6.4 and 10.6 µm). It was shown that single emission-emission lasers readily combine into a single port across a wide spectral band within the MIR. Even the power characteristics of the individual QCLs are well preserved and closely resemble the individual gain curves of the used OCLs. For evaluation of the optical power transmitted via the iBEAM all three OCLs were tuned to an emission wavelength of 1649 cm⁻¹ (6.1 μ m) (Fig. 3(c)). The power spectrum of all three lasers combined closely resembles an envelope function encompassing the addition of the emission spectra of each laser. In addition to spectral evaluation, the beam profile of the beam emitted from the output port of the iBEAM was evaluated with a DataRay IR-BB-7.5 beam profiler. The emitted beam profile shows a rectangular diffraction profile resulting from the cross-section of the hollow waveguide channel, which is superimposed by a spherical diffraction pattern due to the circular aperture of the light channel. The elongated vertical diffraction pattern derives from higher order modes of the vertically polarized radiation propagating through the channel.



Fig. 3. a) Broad-band transmission behavior of an aluminum-based iBEAM. b) Spectral characteristics when combining three individual QCLs fiber-optically into ports of the iBEAM. c) Power characteristics when combining three individual QCLs fiber-optically into ports of the iBEAM tuned to the same emission wavelengths. d) Near field beam profile as emitted from the output port. The inset in d) shows a simulated beam profile (COMSOL FEM simulation) revealing high order mode propagation within the air-filled hollow waveguide core.

5. Conclusions

A multi-port beam combiner based on substrate-integrated hollow waveguide structures (i.e. iBEAM) has been developed and characterized confirming excellent conservation of the spectral and power characteristics of individual mid-infrared emitting quantum cascade lasers at a single output port. In addition, efficient fiber-coupling of the light sources to the iBEAM enabled unprecedented flexibility for adapting this concept to a wide variety of application scenarios. Fiber-to-hollow-core-channel coupling losses of 6.4(9) dB were derived. Propagation losses of 0.6(2) dB/cm at a wavelength of 5.8 μ m (1720 cm⁻¹), and of 1.5(4) dB/cm at a wavelength of 10.6 µm (943 cm⁻¹) confirmed adequate characteristics for shortrange propagation of MIR radiation as intended for integrated beam combining purposes. Fabricating the iBEAM from solid aluminum provides excellent reflectivity throughout a broad spectral window, in fact from the deep UV to the THz and has been demonstrated in the present study for the 3-12 µm regime. The obtained properties of the combined beam ideally meet the needs of chem/bio-sensing scenarios in MIR laser spectroscopy, which frequently required addressing multiple molecule-specific wavelengths spread across a wide spectral band. Next to its utility in chem/bio MIR sensors, it has been shown that the iBEAM device is suitable up to CO_2 laser frequencies (i.e. 10.6 µm) as required for high power beam combination in manufacturing purposes. Last but not least, M (4.7 μ m), N (10 μ m) and Q (20

 μ m) bands are readily accessible enabling efficient beam combing via an iBEAM in infrared astronomy.

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Disclosures

The authors declare that there are no conflicts of interest related to this article.

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