Evaluation of the efficiency of the mid-IR heterodyne spectrometer using hollow fibers

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The mid-IR laser heterodyne spectroscopy provides high spectral resolution > 10^6, which is much greater than other direct spectroscopic measurements. This technique combines an IR source signal from the observing target and an IR laser (a quantum cascade laser (QCL) and/or a CO_2 gas laser) as the local oscillator (LO). We have developed the mid-infrared laser heterodyne spectrometer MILAHI (Mid Infrared LAser Heterodyne Instrument) mounted on our dedicated Tohoku 60 cm telescope (T60) at the summit of Mt. Haleakala, Hawaii. This instrument has successfully operated for the measurements of Venusian and Martian atmosphere (Nakagawa et al., 2016; Takami et al., 2020).

In the current system, two beams are combined at a ZnSe beam splitter and then focused onto a HgCdTe photomixer. In this scheme, a precise optical alignment is highly required to combine two beams. Since the wavelength of a single feedback (FB) QCL is restricted within the range of several cm^{-1}, switching LOs is needed for wider wavelength coverage. A CO_2 gas laser covers some parts of the wavelength ranges of 9-12 um and four QCLs provide the wavelength ranges of 7.43-7.44 um, 7.71-7.73 um, 9.54-9.59 um, 10.28-10.33 um are installed in MILAHI as LOs. However, smooth switching mechanism of those LOs enhances the complexity of this system. We tried to simplify those optics with mid-IR transmissive hollow fibers.

There is few optical fiber which has a high transmittance at the wavelengths longer than 2 um. Recently mid-IR (5-20 um) transmissive hollow fibers has been developed by Tohoku University (e.g., Matsuura et al., 1995). The fibers are made of glass tubing whose inner diameter are 1 mm. Inner surface is covered by a conductive Ag layer covered by a dielectric AgI layer. With this fiber, we have tested the transmittance, heterodyne capability, and coupling/division of light.

(1) Transmittance of 0.5dB/m at 10.6 um was reported in previous studies (e.g. Matsuura et al., 1995). At the moment, we have achieved about 85% transmittance with a 300 mm hollow fiber at 10.3 um from our laboratory measurements. Since the transmittance strongly depends on the incident angle of the light, better transmittance might be possible by improving the alignment.

(2) We confirmed the applicability of hollow fibers to mid-IR heterodyne system. The heterodyne spectroscopy with hollow optical fiber resolved the spectral feature of the narrow

laser emission line. Achieved system noise temperature was less than 3,000 K, which was only twice the quantum limit and almost the same as that in the system without hollow fibers.

(3) We also confirmed the applicability of the fiber coupler to mid-IR heterodyne system. The fiber coupler enables coupling or splitting lights by combining fibers directly for the hollow fibers (Tamura et al., 2017).　The fiber coupler can provide downsizing, weight saving, and high stabilization of the instrument. Those are essential progresses for this instrument optimizing to space-born missions.

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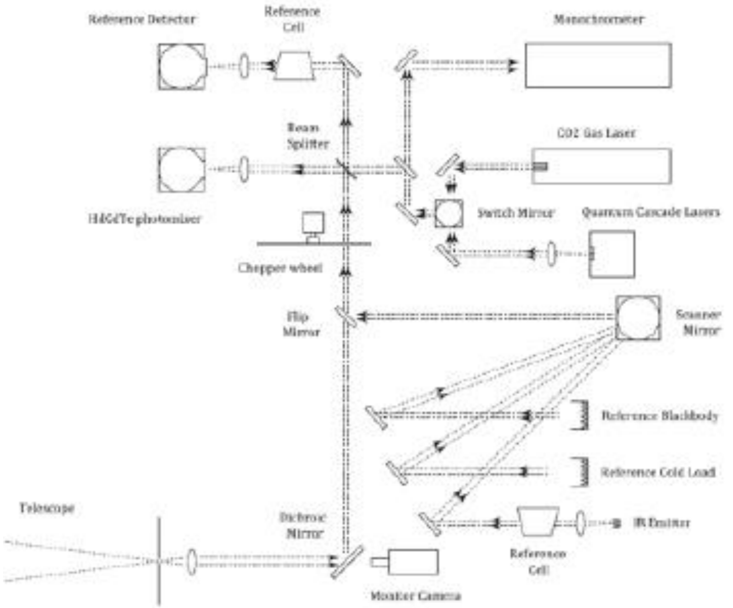


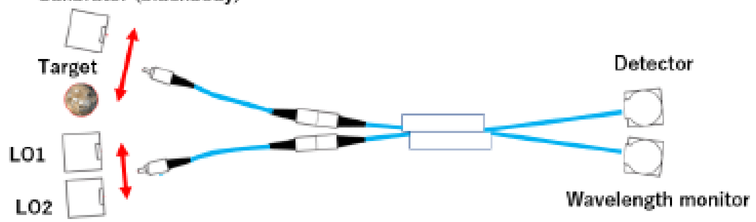
(Nakagawa et al., 2016)

Introduction

MIR heterodyne spectroscopy enables an unprecedented high-spectral resolution at 7 – 12 micron with resolving power > 10^6 and sensitivity close to the quantum limit[1]. Notable successes on Venus, Mars, Jupiter, Titan, and Earth have been accomplished by ground-based observations[2,3,4], meanwhile the space-born IR heterodyne spectrometer has never been done so far due to its volume, weight, and a precision of optical alignment. Rodin et al. (2015) proposed a compact, lightweight multichannel laser and heterodyne spectrometer for the ExoMars landing platform in near-IR by using a bundle of single fibers and directional couplers[5]. The solution for MIR, however, is still open issue.

The hollow optical fibers developed by Tohoku Univ. transmits electromagnetic wave with any wavelengths from X-ray to Terahertz-wave with low transmission losses (0.5 dB/m at 10 micron)[6].

Simplify the optics



Future solar exploration missions

Here we demonstrate the feasibility study of hollow optical for MIR heterodyne spectroscopy for future solar system exploration missions.

Experimental Setup

An IR source from the target was combined with a laser local oscillator (LO) and was focused onto a MCT photodiode mixer. The resultant intermediate frequency (IF) in the radio region preserves the intensity and spectral information of the IR spectrum.

In Setup (a) and Setup (b), two beams were combined by conventional beam splitter. A single 30cm-length hollow optical fiber was applied to lead the LO and the target to the beam splitter. Schematics of the experimental setup are shown in Figure 1.

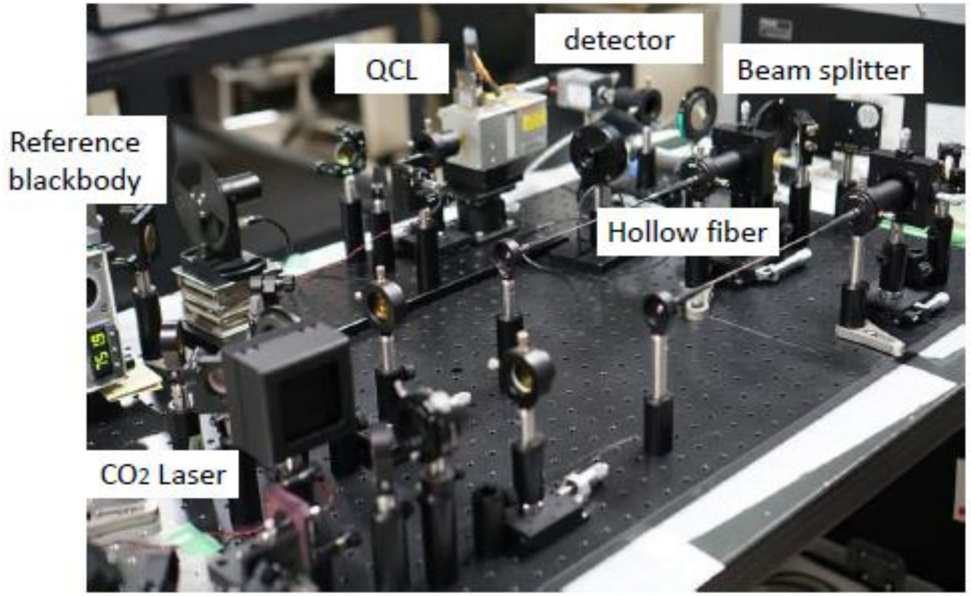
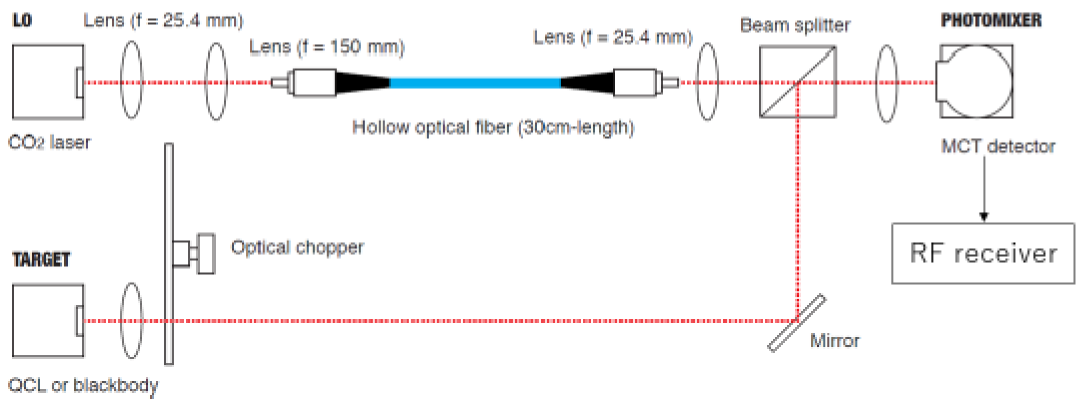


Fig.2 View of the optics and fiber of the experimental setup (b). The hollow optical fibers were set exchangeable with commercial SMA connectors.

Setup (a) : Fiber was applied to lead the LO.



Setup (b) : Fibers were applied to lead the LO and the target.

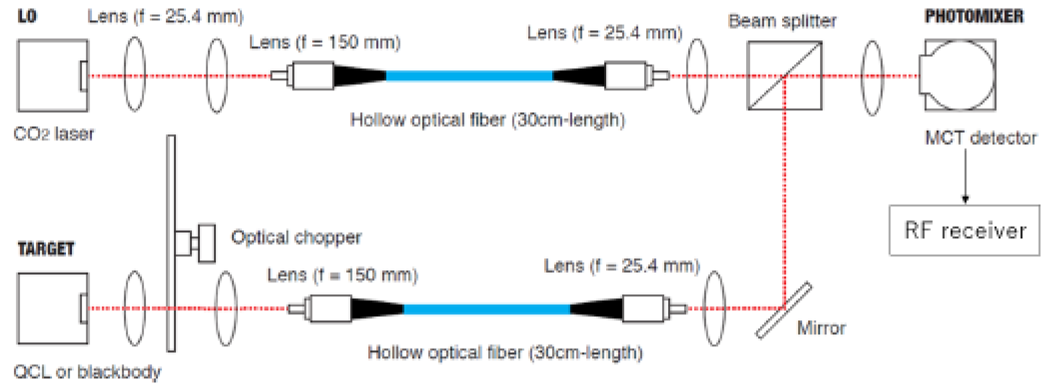


Fig.1 Optical configuration of the experimental setup. CO2 gas laser as the LO. A room-temperature-type MCT generates an IF signal with a bandwidth of 250 MHz. A calibrated blackbody was applied for the hot load (400 degC). A room-temperature-type QCL was also applied for the target in order to assess the spectral feature. The backend spectrometer of 1.5 GHz resolved in 1Hz.

In Setup (a), fiber was applied to lead the LO.

In Setup (b), fibers were applied to lead the LO and the target.

Results

Transmittance of the hollow fiber

The transmittance of the hollow optical fiber including the commercial SMA connectors was typically measured in the system to be ~85% (up to 94% in the experimental setup) to a coherent light from CO_2 laser or QCL. The measured output of a coherent light suggests an improvement comparing with conventional PIR fibers. As for the transmittance to broad and incoherent light from the reference blackbody, the transmittance was typically ~10% . Transmittance is highly affected by incident angle of the beam. So, transmittance to broad and incoherent light will be improved for use on the large F-value telescope. Work on improving transmittance continues.

Setup (a) & (b) CO_2 laser + QCL

Figure 5 shows the spectral features of the QCL emission line obtained at 0.5s interval by heterodyne measurements on the system shown in Fig.1. Laboratory measurements with hollow optical fiber show a quite well match with our previous setup without fiber[7].

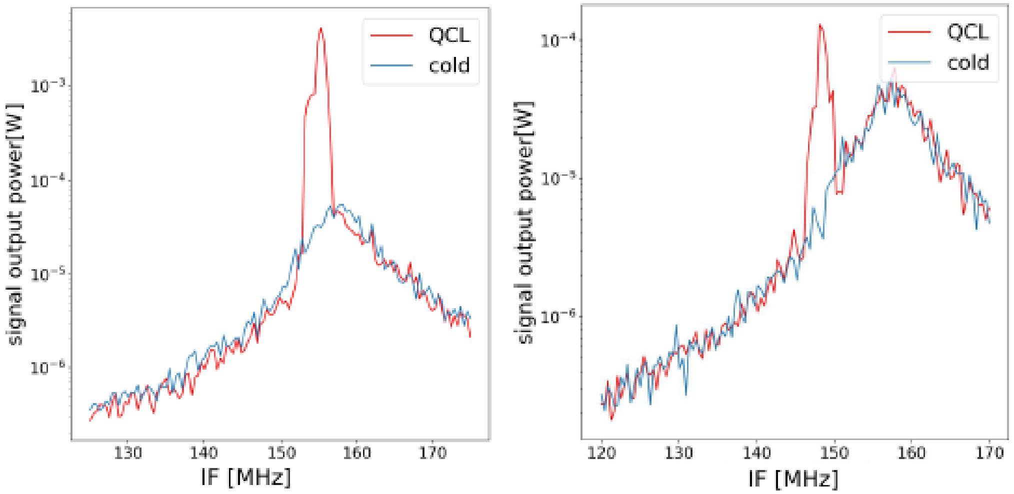


Fig.5 An example of the emission spectrum of the QCL obtained by heterodyne measurement with a CO_2 laserbased heterodyne systems shown in Fig.1 at 10.3 micron at 0.5s interval. The obtained spectra by the spectrometer with QCL (red) and with ambient room temperature load (blue). The emission spectrum in the left figure was obtained in the Setup (a) and the right one was obtained in the Setup (b).

Setup (a) CO_2 laser + blackbody

The typical system noise temperature achieved less than 3000 K at 10.3 micron, as shown in Figure 6. This is only ~100% above the quantum limit. The difference between spectra with and without fiber on the LO light path was not significant.

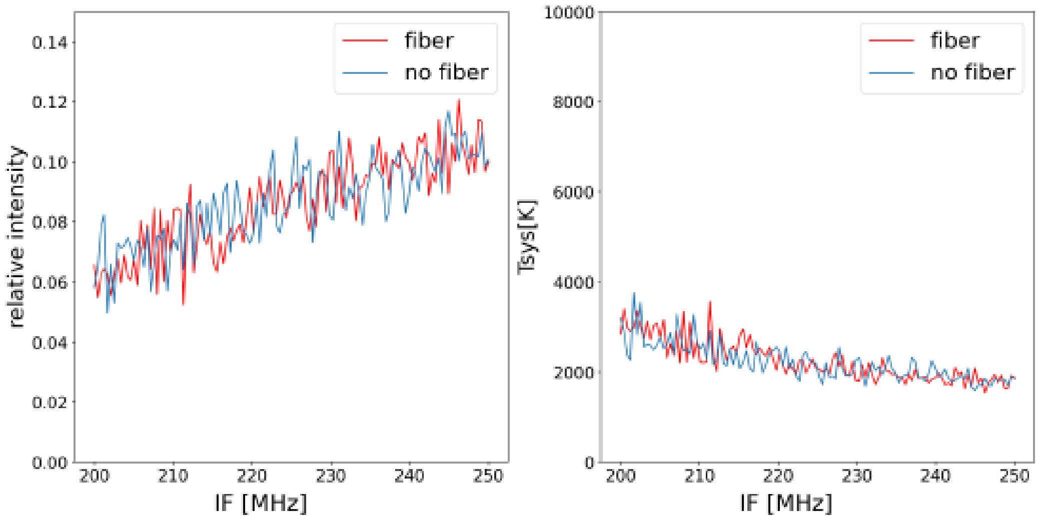


Fig.6 The spectra of the reference blackbody obtained by a CO_2 laser-based heterodyne system shown in Fig.1 as Setup (a) with hollow optical fiber (red) and without fiber (blue) (left). System noise temperature at 10.3 micron in Setup (a) with hollow optical fiber (red) and without fiber (blue) (right).

Setup (b) CO_2 laser + blackbody

The typical system noise temperature in Setup(b) was larger than 20000K at 10.3 micron. Larger system noise temperature is due to larger loss of the fiber to broad and incoherent light from the reference blackbody. Transmittance to broad and incoherent light can be improved by optimizing incident angle of the beam.

Experimental Setup

We also tested applicability of new fiber coupler. In Setup (c), two beams were combined by the fiber coupler. A single 60cm-length hollow optical fiber was applied to lead the LO and the target to the fiber coupler. Schematic of the experimental setup is shown in Figure 3. Table 1 shows branching ratio and transmittance of the fiber coupler.

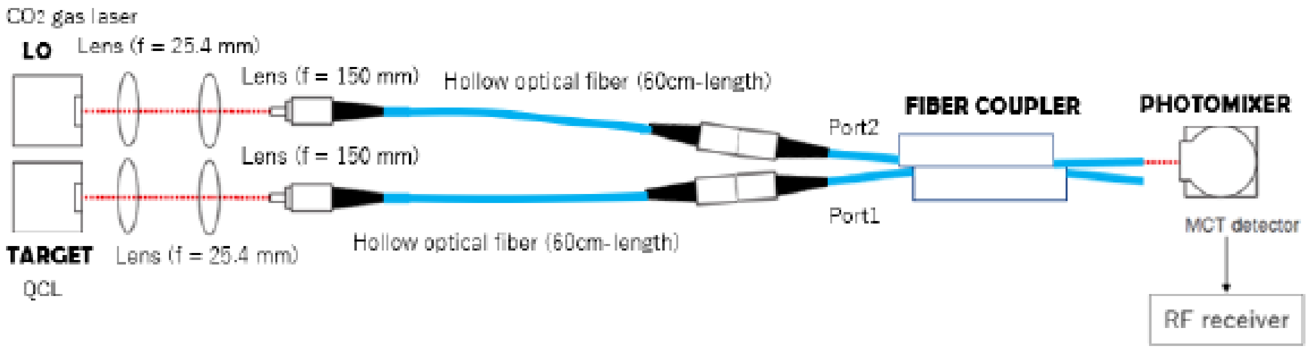


Fig.3 Optical configuration of the experimental setup. CO2 gas laser as the LO. A room-temperature-type MCT generates an IF signal with a bandwidth of 250 MHz. A room-temperature-type QCL was applied for the target in order to assess the spectral feature. The backend spectrometer of 1.5 GHz resolved in 1Hz.

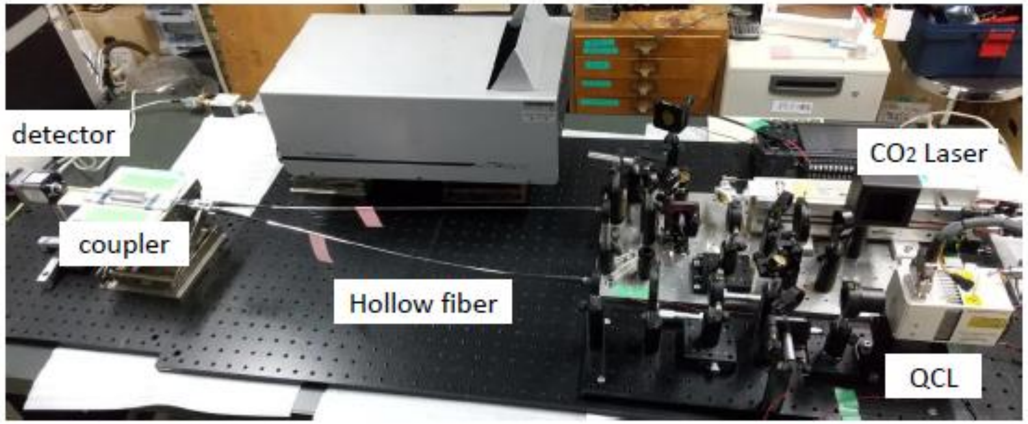


Fig.4 View of the optics and fiber of the experimental setup (c). The hollow optical fibers and the fiber coupler were connected with commercial SMA connectors.

Input port	Bar port	Cross port	Branching ratio	Transmittance
Port1	44.6%	6.3%	8:1	50.9%
Port2	56.0%	7.7%	15:2	63.7%

Table 1 Branching ratio and transmittance of the fiber coupler for CO2 gas laser.

Results

Setup (c) CO_2 laser + QCL

Figure 7 shows the spectral feature of the QCL emission line obtained on the system shown in Fig.3. The spectral feature of the QCL emission shows a quite well match with our previous setup without fiber.

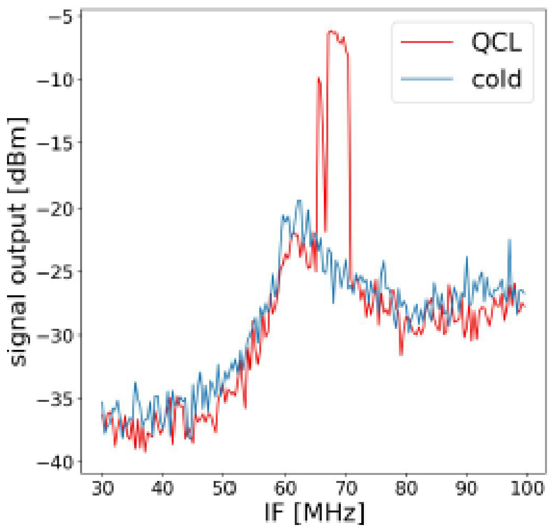


Fig.7 An example of the emission spectrum of the QCL obtained by heterodyne measurement with a CO_2 laser-based heterodyne system shown in Fig.3 at 10.3 micron. The obtained spectra by the spectrometer with QCL (red) and with ambient room temperature load (blue) .

Conclusions

We demonstrated a new design hollow optical fiber suitable for use on an IR heterodyne spectroscopy in mid-infrared wavelength region. The spectral feature of the laser emission line and the system noise temperature obtained by heterodyne detection with hollow optical fiber were confirmed by a laboratory measurement. We also obtained the spectral feature of the laser emission line by the heterodyne detection with fiber coupler by a laboratory measurement.

1. **The transmittance of the hollow optical fiber was 85% at 10.3 micron to a coherent light.**
2. **We confirmed applicability of hollow optical fiber for heterodyne spectroscopy.**
3. **The hollow optical fiber allows heterodyne detection with a sufficient efficiency when the fiber leads coherent light.**
4. **We also confirmed applicability of the fiber coupler for heterodyne spectroscopy. .**

Further investigation is required for use on the extended light source with the large F-value telescope from quasi-infinity distance.

The present study permits simplified fabrication, provides even more weight reduction.