Quasi-Optics for 640 GHz SIS Receiver of International-Space-Station-Borne Limb-Emission Sounder SMILES

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Abstract

We are developing quasi-optics for a 640 GHz limb emission sounder SMILES to be based on the International Space Station (ISS). SMILES is a heterodyne spectrometer and will use SIS mixers first time in space to detect trace molecules in the stratosphere. The engineering model of the optics has already been manufactured. We have demonstrated key functions such as an image-band rejection better than 20 dB, feeding Gaussian like beam pattern to antenna from back-to-back horn, supplying balanced LO power to the two SIS mixers, and radiation-shielding capability of 40 dB against external interference radiation below 26.5 GHz. We also demonstrated that these optical performances could be maintained over the vibration during launch and temperature variation on orbit. These performances almost satisfy specifications. The optics will be assembled into the engineering model of 640 GHz receiver system in 2003.

1. Introduction

We are developing a quasi-optics for a 640 GHz heterodyne receiver for SMILES. SMILES is a limb emission sounder to observe thermal emission from stratospheric molecules related to ozone depletion from the International Space Station (ISS). It is equipped with SIS mixers first time in space. The SIS mixer is known as the lowest noise device for heterodyne detection in 640 GHz band and it makes possible to detect extremely trace molecules (e.g., BrO) as well as precise global mapping for distribution of trace molecules (e.g.,O_3, ClO, and HCl). The ISS presents a number of engineering challenges. The receiver must cope with vibration during launch, large temperature variation while in space, and electrical interference from telecommunications signals on the ISS. The sensitivity of the receiver is determined by the noises of mixer plus amplifiers as well as the losses in the input optics. The sensitivity may also be limited by spurious noise due to interference radiation and standing waves. The receiver optics for SMILES is designed to minimize these problems while maintaining the input loss as low as possible.

In this paper we describe the design of the receiver optics and show some experimental results of its key functions.

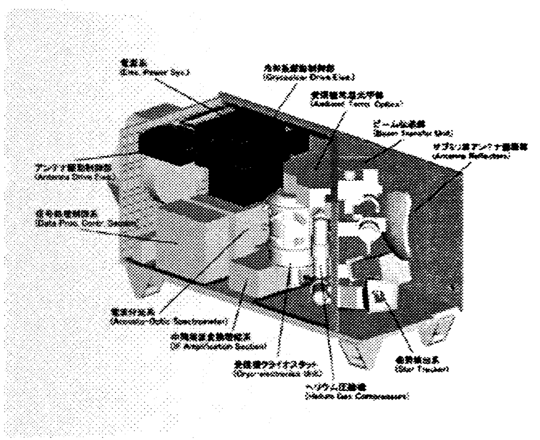

Fig. 1 Schematic view of SMILES as a payload of the Exposed Facility of Japanese Experiment Module of the ISS.

2. Overview of Optics for SMILES

2.1 640 GHz SIS Receiver for SMILES

The SMILES is a payload of the Exposed Facility of the Japanese Experiment Module (JEM) on the ISS. It is packed in a box with a dimension of 1.9 m x 1.0 m x 0.5 m and a mass of 500 kg as shown in Figure1.

We show block diagram of the 640 GHz receiver of the SMILES in Figure 2. A mechanically scanning a 40 cm x 20 cm offset Cassegrain antenna receives emission from the stratosphere. The receiver optics is composed of an ambient temperature optics (AOPT) and a 4K-cooled optics (COPT). The receiver optics provides quasi-optical coupling between antenna optics and SIS mixers, and has a function to supply local oscillator (LO) signal to two SIS mixers operating in single sideband (SSB) [1], and to shield the receiver against external interference radiation [2].

The mixer output of the first intermediate-frequency (IF) signal (11-13GHz) is amplified by a chain of 20K-cooled and 100K-cooled amplifiers [3]. A mechanical 4K refrigerator cools down the cryo-electronics (CRE)[4]. The IF signal is further amplified and down-converted into the second IF frequency band of 1.55-2.75 GHz by an ambient temperature amplifier (AAMP) and an IF amplification section (IFA) followed by two acousto-optic spectrometers [5].

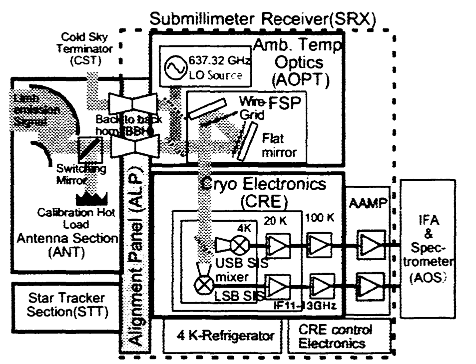

Fig.2 Block diagram of 640 GHz receiver for SMILES.

2.2 Back-to-Back Horn

The receiver optics is connected to the antenna (ANT) optics via two back-to back horns (BBHs) [6]. Figure 3 shows the picture of two BBHs on engineering model of AOPT. The BBH for SMILES is an overmoded waveguide with corrugated wall whose apertures on both ends are designed to match input and output beams. The BBH has two outstanding functions in the optics.

One function is electromagnetic shielding capability. The narrow inner diameter of the waveguide of the BBH works as a cut-off filter, while keeping small loss because the BBH acts as a oversized corrugated waveguide at frequencies around 640 GHz. Electromagnetic interference radiations within the SMILES IF band (11-13 GHz) might cause spurious signals in observed spectra. We protect the SIS mixers and cooled amplifiers against the interference radiation of 2 V/m below 26.5 GHz expected on the ISS. We require radiation shielding more than 54 dB for the SIS mixer and the amplifiers to suppress the spurious signal below 1.5 K. The main-frame structure of the SMILES payload provides a 14 dB radiation shielding, so the shielding requirement for the cryostat placed within the frame is relaxed to 40 dB. The cryostat is designed to provide >40 dB shielding when it is connected to the AOPT by metallic bellow around it. Thus the frame of the AOPT is required to have shielding capability of more then 40 dB. The shielding requirements for the BBH is 54 dB that is lager than the requirement for the frame since the BBH is opened to outer space of the main frame for the SMILES though the alignment panel.

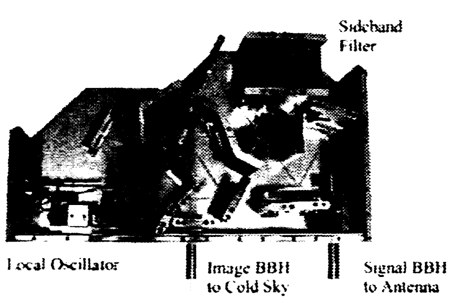

Fig. 3 Picture of engineering model of AOPT.

Second function of the BBH is to separate the basic design of optics at each side of the BBH aperture. The AOPT and antenna optics is placed on opposite side of the alignment panel that is a reference plane for all the optical components. Thus we can specify the position of the BBH and the beam parameters at the aperture of the BBH as interface conditions for basic design of the optics. The separation in design is useful for fabrication of a big system where different groups develop several components.

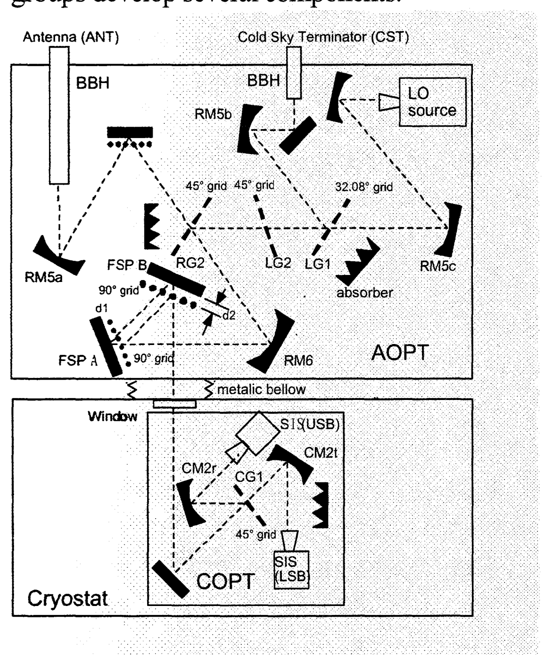

Fig. 4. Schematic diagram of the optics.

3. Single Sideband Filtering and Local Oscillator Signal Diplexing

3.1 SSB Filtering

We show the schematic diagram of the receiver optics in Figure 4. One feature of the optics of the SMILES is operation of two SIS mixers simultaneously in SSB mode for the upper sideband (USB), 649.12-650.32 GHz , and lower sideband (LSB), 624.12-625.52 GHz. An image rejection ratio larger than 15 dB is required for the SSB filter. We developed a new type of SSB filter consisting of Frequency Selective Polarizers (FSP). The FSP is composed of a flat mirror and a wire grid. The FSP-type SSB filter has two advantages over the conventional Martin-Puplett interferometer (MPI) in that it is almost free from undesired residual return reflection which causes harmful standings waves, and it can be made thermally stable for fixed tuned applications [7,8].

The new SSB filter is composed of two FSPs, a polarizing grid (RG1) in AOPT, and an analyzing grid (CG1) in COPT (Figure. 4). It is a four ports device for lineally polarized beams. It is an interferometer working in the same operational principle for the conventional MPI [8]. The orientation of a the grid of FSP A should be parallel to that of the grid of FSP B, and be 45° tilted that respect to the orientation of the grids of RG1 and CG1 in the projected plane perpendicular to the direction of propagation. The +45° and -45° polarized beam ports are assigned to the SIS mixers for LSB and USB, respectively. The grid RG1 in AOPT selects a +45° polarized beam as the signal from stratospheric emissions via BBH for ANT. The –45°polarized beam in the AOPT is assigned for cold sky termination (CST) signal plus LO signal. The cold sky port is terminated to cosmic back ground radiation via BBH for CTS. The grid-mirror spacing (d1and d2 of Figure 4) of the FSPs determines the power coupling characteristics between these ports. We chose the spacing so that one of the SIS (USB) mixers couples to the signal port in USB while it couples to the CST port in LSB. The other SIS mixer was tuned for detection of the signal in LSB automatically by the choice of the separation.

3.2 Diplexing of the LO Signal

The AOPT also serves as a diplexer for LO signal. There are several quasi-optical dilplexing methods. The dielectric thin film coupling is the simplest diplexer. However loss at the film cannot be ignored for the sensitive detector for SMILES. An additional MPI could be used for diplexing without introducing additional loss. However it requires additional optical components that may increase possibility of troubles in space.

We use a freestanding wire grid as a diplexer. The 637.32 GHz LO source on the AOPT is composed of 106.22 GHz fixed tuned Gundiode followed by doubler and tripler. The wire grid LG1 combines signal from the LO source and signals from the image terminating CST (Figure 4). The power coupling ratio of LO source to the signal is determined by the orientation of the grid wire of LG1 relative to that of RG1. The coupling ratio should be minimized as far as enough power is supplied for the SIS mixers, since a large coupling ratio increases the effective temperature of the image terminator and increases standing waves between the SIS mixer and the LO source. We designed to couple 5% of the output power of the LO source to the signal path. Absorber for grid RG1terminates the remaining 95% power of the LO signal.

The LO signal coupling balance to the SIS mixer is determined by the bandpass characteristics of the SSB filter. We supply the power of LO signal equally to the two SIS mixers. Two SIS mixers for USB and LSB are designed identically, so the same amount of LO signal power is required for operation. The cross polarization leakage of the grid RG1 is a possible source of the frequency shift of the SSB filter. Thus we inserted a cross polarization clearance grid LG2 in front of the grid RG1. The cross polarization could be reduce by the tandem of wire girds set to the same projected angle.

3.3 Measurements of Bandpass Characteristics

We measured the bandpass characteristics of the engineering model of AOPT [9]. Bandpass and image rejection characteristics between the antenna-side BBH input and the COPT-side output port were measured for the LSB or USB port of the COPT by selecting proper linear polarization. Figure 5 shows measured bandpass and image rejection characteristics around the LSB and USB. In this figure, image rejection ratios better than 20 dB are achieved over the LSB and USB simultaneously. The internal reflections within the AOPT are also measured [9]. The reflection at the FSP was found to be below detection limit of –60 dB. This confirms the low reflectivity of the FSP. We conclude that the new SSB filter based on the FSPs satisfies the requirements for SSB filtering for SMILES.

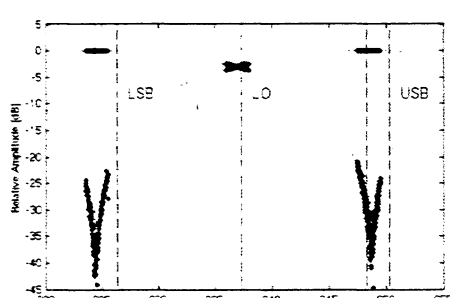

Fig. 5 Measured bandpass characteristics of AOPT.

The measured cross-over characteristics around the LO signal frequency of 637.32 GHz are shown in detail in figure 6. It shows balanced coupling of the LO signal with imbalance of 0.6 dB. This good balance was realized by good machining of mirror-grid distance and reduction of cross polarization leakage in polarizing grid (RG1 plus LG2 in Figure 4) of the FSP based SSB filter. We checked that removal of cross polarization cleaning grid LG2 increased the coupling imbalance from 0.6 dB to 6dB. We also measured 5% coupling efficiency of the LO source to the COPT by using a submillimeter wave power meter. The power meter received 25μW of LO signal at the COPT window of the AOPT when the LO source was operating in the AOPT. It corresponds to the 5% of the LO signal output power of 0.5 mW that is measured for engineering model of the LO source. We consider that the 5% LO signal power coupling to the SIS mixer with imbalance of 0.6 dB satisfies the requirements of the diplexer for SMILES.

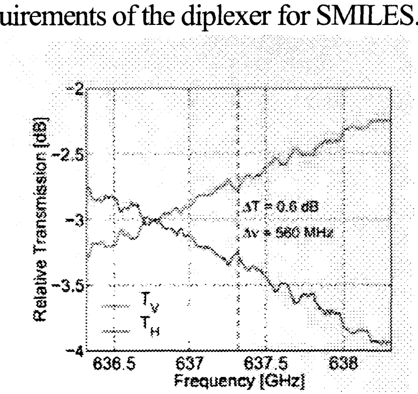

Fig.6 Measured band pass characteristics around the LO frequency.

4. Transformation of Beam

4.1 Design of the Beam Transformation

The loss in the input optics is specified as below 1.7 dB for SMILES to realize an SSB receiver noise temperature below 500 K. We use focusing mirrors and horns for quasi optical beam transformation elements that are superior to other beam propagation method in 640 GHz. Several attentions were paid for further reduction of the losses in quasi-optical design such as employment of large aperture mirrors to keep beam truncation level below –40 dB in terms of the fundamental Gaussian mode, and small off axis angle for suppressing generationof cross polarization.

There are three requirements for the design of the beam transformation for SMILES. We designed the optical parameters based on the analyses of the fundamental Gaussian mode. One restriction is size of the window of the cryostat. The smaller one is better for the cryogenics. The cryostat and refrigerator is designed to allow the cryostat window size not more than 25 mm in diameter. Second restriction is the size of diameter of the BBH. The diameter of the BBH should be smaller than 6.4 mm so as to work as a cutoff filter against radiations below 26.5 GHz. Final requirement is production of image of the mixer horn at the aperture of the BBH. It is known that Gaussian beam parameters become frequency independent at two image planes. The frequency independent beam reduces losses due to miss coupling of the beam at the apertures of the horns. It also reduces the reflection there.

Name	Distance	Focal length
Mixer horn	0	
CM2	50.00 mm	48.65 mm
RM6	530.669 mm	134.29 mm
RM5	825.669 mm	48.92 mm
BBH	893.859 mm	

Table 1 Position and focal lengths of focusing mirrors.

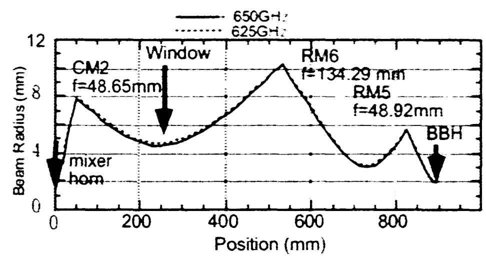

Fig.7 Propagation of quasi-optical beam from mixer horn to BBH. The radius shows 1 e amplitude radius of the Gaussian beam.

We optimized positions and lengths of the three focusing mirrors to realize these requirements as summarized in Table1. We show beam transformation along the optical path from the mixer horn to the BBH for 625 GHz and 650 GHz that are representative for LSB and USB in Figure 7. The two lines are almost overlapping. We confirmed that the Guassian beam parameter of radius of curvature R and beam radius W is identical for over the frequency range between 624.12 and 650.32 GHz at the apertures of the BBH (W=1.9 mm, 1/R=0) and the mixer horn (W=1.45 mm, R=16 mm). The beam waist is placed around the window of the cryostat, although there is negligible small difference for the position and size of the beam waist between the two beams. The beam transformation is designed identical for signal path (SIS-FSP-BBH for ANT) and cold sky path (SIS-FPS-BBH for CST). The frequency independent beam condition is relaxed for LO path (SIS-FSP-LO) since LO signal frequency is fixed at 637.32 GHz.

4.2 Beam Pattern Measurements

We evaluated the design of beam

transformation by the output beam pattern from the BBH. We measured the phase and amplitude of the beam from the BBH by AB mm vector network analyzer [9-11]. We placed the detector with a focusing mirror and wire grid at the COPT port of the AOPT that simulates the COPT. We radiated the BBHs by test signal from another horn and scanned it.

We show a beam pattern for a BBH for ANT measured at 649.32 GHz in Figure 8 and Figure 9. There is a good agreement between the theoretical calculations and measured one down to –20 dB. The theoretical pattern simulates the beam from an ideal corrugated horn by CORRUG. This good agreement suggests that our optical design and manufacturing process are good. There is small distortion below -20 dB levels. The distortion in –20 dB levels is close to the boundary of a level above which the antenna beam efficiency was degraded by 1%. We consider that the measured pattern is acceptable for feeding the antenna.

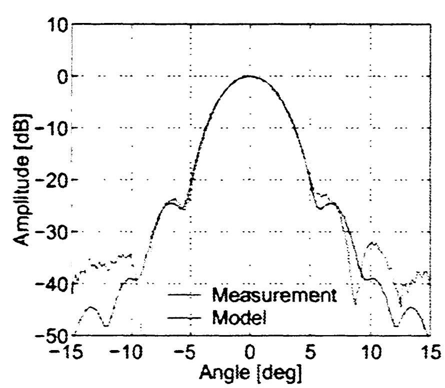

Fig. 8 Measured beam pattern of amplitude from a BBH.

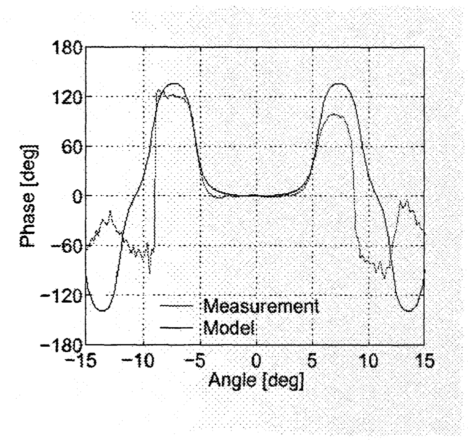

Fig. 9 Measured beam pattern of phase from a BBH.

5. Shielding of Interference Radiation

5.1 Shielding of the Frame Box of Optics

The frame box of AOPT is required to have shielding capability more then 40 dB below 26.5 GHz. The basic structure of frame box of AOPT is aluminum plates (Figure 3). We inserted a conductive rubber tube when we stuck the plats together to improve the shielding. There are six feedthoughs in the frame of the AOPT for biasing cables for LO source. We put Indium for mounting of the feedthoughs. These shielding techniques should be good enough for the 40 dB requirement of the frame box of the AOPT.

5.2 Measurement of Radiation Shielding

We evaluated the radiation shielding capability of the engineering model of the AOPT alone. The COPT-side window was shielded by an aluminum plate to simulate the shielding provided by the cryostat and the bellow. The basic procedure of the shielding evaluation is to measure the shield level inside the AOPT when it is irradiated from outside. We used a level as reference one when we exposed the emitting probe of the test radiation to the detector. The received power should decrease when we put the probe in the AOPT. We define a shielding capability as the amount of the decreased power. We swept the frequency of the test radiation from 2 GHz to 20 GHz with a frequency step of 0.1 GHz.

We show measured results of the shielding of the AOPT for three different orientations in Figure 10. It shows the AOPT has shielding capability more than 40 dB for the measured frequency range of 1 to 20 GHz. This shielding level is good enough for our requirement of >40 dB.

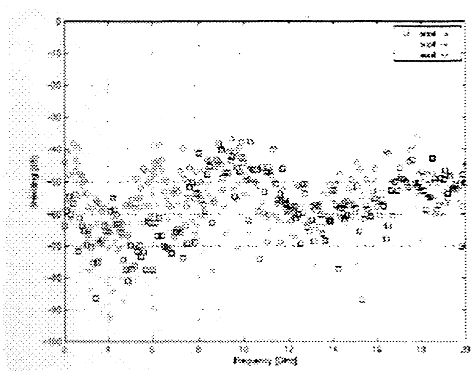

Fig. 10 Measured shielding capability of AOPT.

6. Environmental Conditions as a Space Instrument

The optics of the SMILES is designed to survive the vibration during launch and temperature variation on orbit. SMILES will be transported to the ISS by Japanese HII Transfer Vehicle launched by the HII rocket. The AOPT is placed on the alignment panel of the payload of the SMILES (Figure 1). The AOPT is required to survive 15 Grms level vibration for qualification test on ground. The test vibration level of the COPT is 26 Grms that is higher than the test level for the AOPT because there is some amplification of the vibration in the supporting mechanism of the 4Kstage for COPT. The AOPT is also required to survive temperature variation between –40 degC to +60 degC. The circulating coolant supplied by JEM controls the temperature of the AOPT between 15 degC to 40 degC on normal operation. We tested the variation of the optical performances before and after the vibration and thermal cycling test.

The null position of the bandpass characteristics is good probe for examining the change in optical performance since it is sensitive to the small change in configurations such as grid-wire distance and orientation of optical elements. We show how the null poison changes over the test in Figure 11. There is small change in the frequency. The 200 MHz shift is close to the measurement error. The value of frequency shift is acceptable for SMILES in the senses that this shit will not degrade achieved image rejection ratio better than 15 dB and balanced LO signal coupling to the SIS mixers. We conclude that the optics for SMILE passed the vibration and thermal cycling test.

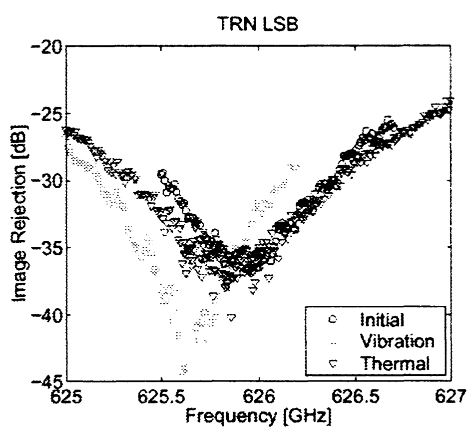

Fig. 11 Variation of null position of the band pass characteristics over the environmental test.

7. Conclusion

We have fabricated engineering model of the receiver optics for International Space station (ISS)-borne limb emission sounder SMILES. We showed that antenna feeding beam pattern agreed with theoretical calculation down to –20dB. We showed image rejection of 20 dB at the USB and LSB using a par of Frequency Selective Polarizer (FSP) as a SSB filter. We showed the balanced LO injection to the two SIS mixers. The internal reflection within the optics is very low < -50 dB for the signal path. We showed that shielding capability of the frame box of the optics is better than 40 dB that is large enough to protect SIS mixer and cooled amplifiers from interference radiation expected on the ISS. We showed that the optical performance would not be affected by vibration during launch and temperature variation on orbit. These performances satisfy the specifications imposed on the optics for SMILES. The optics will be integrated into the engineering 640 GHz receiver in 2003. It will show low SSB noise of less than 500 K. The receiver will be refurbished in 2004 for flight model. The launch date of SMILES is postponed from the original schedule due to some reasons for development of the ISS. We expect to operate the SMILES from 2007 for at least one year.

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