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Ultrawideband Spectrally smooth Non-Resonant spherical monopole antenna

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Abstract– **Antenna with spectrally smooth characteristics over several octaves of bandwidth, is required i) for precise measurement of the spectrum of the cosmic microwave background radiation and ii) to detect imprinted features which reflect various physical processes of the evolving universe. We describe the design of a spherical monopole antenna having spectral-smoothness of the order of 1 part in 10^4 in the frequency range 40 – 200 Mhz. The structural parameters have been optimized using electromagnetic modeling for minimizing the effects of surface-current-reflections at the terminations of the antenna. This paper presents the simulation results of the prototype developed to validate the concept along with the measurements.**

1 INTRODUCTION

Radiating structures are generally classified under broadband-category whenever their impedance and radiation characteristics have less dependence on the frequency [1]. Broadband antenna like log periodic structure exhibits wideband performance by resonating over a wide range of frequencies and thereby exhibiting identical impedance and radiation characteristics. Even though structure like this has large bandwidth, its spectral response is not guaranteed to be smooth because of dips at log periodically spaced resonant frequencies.

The scientific requirement of having smooth spectral response without any inflection points in it, is to measure accurately the spectrum of the cosmic microwave background radiation and detect spectral features imprinted in it, in the red shifted frequency range of 40 – 200 MHz. These features are expected to reflect various physical processes of early universe. Since the magnitude of these features is predicted to be orders of magnitude of weaker than the amplitude of the background sky signal, any spurious feature in the spectral response of antenna, would mimic the desired signal confusing the whole process of detection. Therefore, it is necessary that the impedance and radiation characteristics of the antenna be free from these undesirable spurious features.

We have investigated several structural configurations of radiating element, for minimizing the spurious features arising out of discontinuities in the physical dimensions. Rigorous electromagnetic modelling using WIPL-D indicated that a structure made out of a cone and a sphere placed one over the other having dimensional continuity at their interfaces, would have spectral response with minimum spurious features due to the reflection of surface currents at structural discontinuities. Further, spectral features due to the resonance are minimized by operating the antenna in the non-resonant mode. A prototype has been designed based on these observations and tested in the frequency range of 40 – 200 MHz to validate our understanding that structural smoothness and non-resonating mode of operation would result in the smooth response of the impedance characteristics of the antenna over large bandwidth. The loss of sensitivity of antenna at low frequencies due to the non-resonating mode of operation in our design, is compensated by an increase in the sky brightness. Section II describes the motivation behind designing the antenna with smooth spectral characteristics. The investigations carried out through both simulation and experiment, in understanding the effect of various structural parameters and surroundings on the spectral response of the antenna are given in Section III. Fabrication details of the antenna are presented in the section IV and measurements results and challenges faced in achieving stable and accurate measurement are discussed in Sections V. Section VI carries the summary of our work carried out.

2 Scientific Motivation

The motivation in the design of broadband antenna with spectrally smooth impedance and radiation characteristics is to detect minute features in the spectrum of the cosmic microwave background radiation in the frequency range 40-200 MHz

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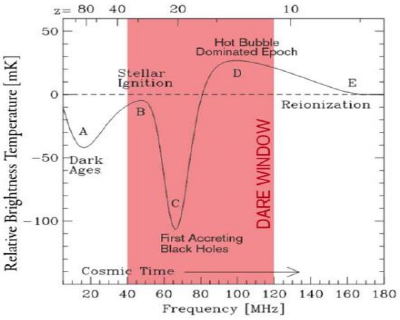

Fig. 1 Sketch of the form of the expected signatures in the cosmic radio background spectrum owing to events during the epoch of reionization [Dare].

These features are understood to be the result of events during the epoch of reionization. The epoch of reionization marks a distinct phase in the evolution of the universe during which the latter underwent phase change from neutral and ionized state. It is during this time that certain physical processes in the evolving universe exerted substantial influence on the environment through electromagnetic radiation resulting in the intergalactic medium of different brightness temperature relative to the cosmic microwave background radiation. This difference in temperature between them is understood to be the reason for the presence of features in the spectrum of CMB radiation. Precise measurement of these features helps us understand better, the events during the epoch of reionization. The spectral nature is predicted to have several turn-over points as shown in Fig. 1 with maximum amplitude of 20-25 mK in emission and 100 mK in absorption. So, it is essential that the spectral response of the measuring instrument be free from features like these in order to ensure that the detection process is not confused by them.

The two main characteristics of an antenna which result in undesired spectral features in its output spectrum are i) impedance match at the input and ii) directive gain. The tolerable limits, on the magnitude and frequency extent of these features are constrained by the expected signatures of the cosmological signal. Of the two, the latter is more important because a feature with an extent in frequency more than the observing band, is tolerable even when its magnitude is larger. This does not confuse the process of detecting the cosmological signal. However, it is preferred to be smaller (few parts in 10^4) than the magnitude of the cosmological signature if its width in frequency domain is smaller than the operating band. From the expected signatures in the cosmic radio background as shown in Fig. 1, if the width of the spectral feature is more than 100 MHz and its amplitude 3 to 4 orders of magnitude lower than the mean level of the sky brightness temperature, it is highly unlikely that, the feature will confuse the detection of the desired signal.

3. **Investigation of smoothly varying fat structures**

Extensive investigation was undertaken through electromagnetic modeling using WIPl-D, to identify a profiled structure having smooth spectral characteristics with undesired feature under acceptable limits. We have studied structures like, conical antenna, tear-drop antenna and spherical monopole antenna [2]. Our study indicated that the spherical monopole antenna when modified to have an input conical feeding section with a tangential intersection with a sphere at its top, exhibited a smooth spectral behaviour. Thus the modified spherical monopole antenna will have : i) a truncated conical feeding section at the input and ii) a sphere on top having tangential intersection with the input cone.

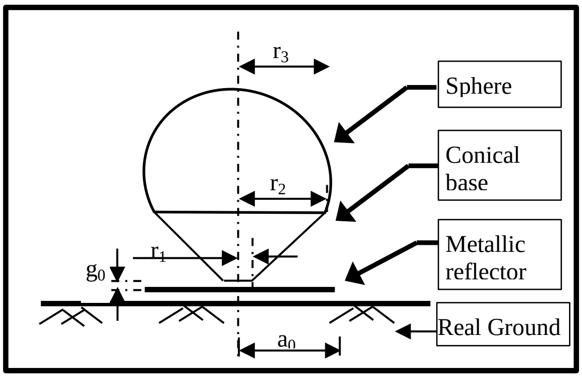

Fig.2 Schematic diagram of the spherical monopole antenna

To meet the desired requirements of amplitude and frequency span of spectral features as mentioned in section II, the structural parameters of the spherical monopole antenna (Ref. Fig. 2) were optimized by adopting the ***Variaiton of Parameters*** technique. Parameters like : i) radius of the metallic reflector – a_0 ii) gap at the feeding section – g_0 iii) radius of the wire used for the excitation –r_0 iv) radii of the input conic section– r_1,r_2 v) length of the conic section – l_1 vi) radius of the sphere and vii) design frequency, were varied one at a time from their default values over a finite range, constrained by the physical realizability of each of them. This was done to understand the effect of each of the parameters on the spectral response of the antenna.

Initially, the monopole antenna was designed to resonate at 200 MHz - the highest frequency of operation. The corresponding wavelength was used as the design wavelength (λ_d = 1500 mm) while assigning electrical dimensions to the antenna structure. The values assigned initially were: i) $a_0 = 0.5*\lambda_d = 750$mm ii) $g_0 = 0.001*\lambda_d = 1.5$ mm iii) $r_0 = 1$mm iv) $r_1 = 0.0045 * \lambda_d = 6.75$ mm v) $r_2 = 0.028*\lambda_d = 42$ mm vi) $l_1 = 0.049*\lambda_d = 73.5$ mm vii) $r_3 = 0.125*\lambda_d = 187.5$ mm. Further, optimization of each one of them was carried out, to minimize abrupt variation in the surface current both on the radiating structure and metallic reflector, to prevent generation of undesired features in the spectral characteristics of the antenna.

Optimization was begun by varying initially the value of the design frequency. The one which resulted in smooth impedance characteristics was used to redefine the electrical dimensions of the structural parameters (Refer Fig.4). Subsequently. radii (r1,r2) of the cone at the feeding section, radius of the sphere (r3) and the radius of the ground reflector (a0) were optimized one at a time (Refer Figs.3-8) to maximize the smoothness of the return loss characteristics of the antenna. The smoothness was quantified by fitting the spectral characteristics by a maximally smooth polynomial function [3]. All the simulations were carried out by keeping the antenna on the ground having $\varepsilon_r = 13$ and $\sigma = 0.005$ S/m. The final optimized structure exhibited smoothness of the order of few parts in 10^5 in its spectral characteristics. The physical dimensions of optimized structure are given in the Table 1.

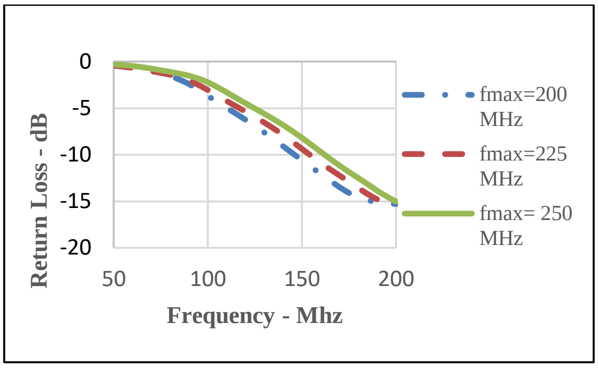

Fig. 3 Effect of design frequency on the return loss characteristics

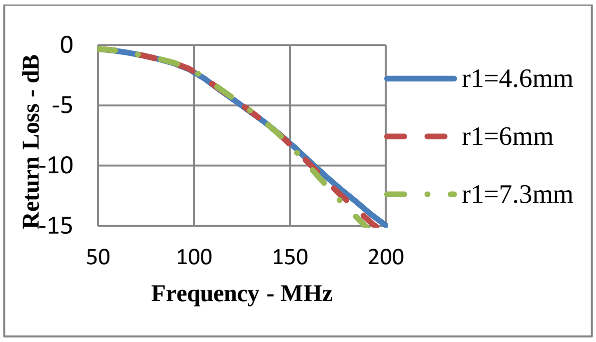

Fig. 4 Effect of change in the bottom radius (r1) of the conical structure on the Return loss

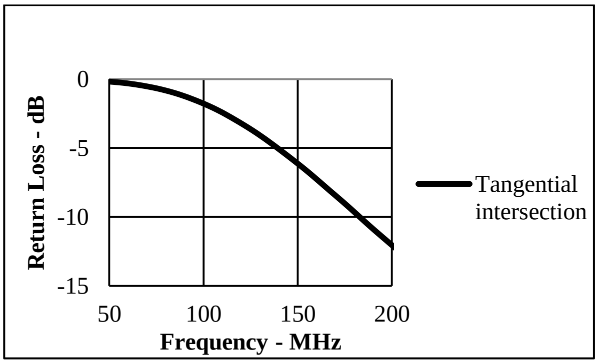

Fig. 5 Return loss when cone intersects the sphere tangentially. The value of r2=102 mm

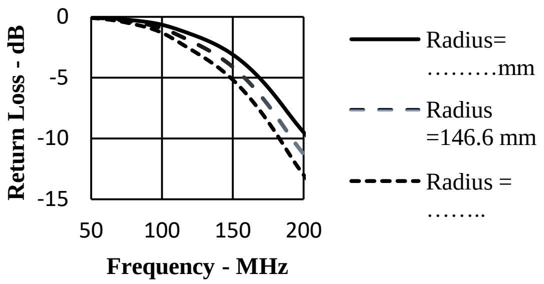

Fig. 6 Effect of Sphere Radius on the Return loss

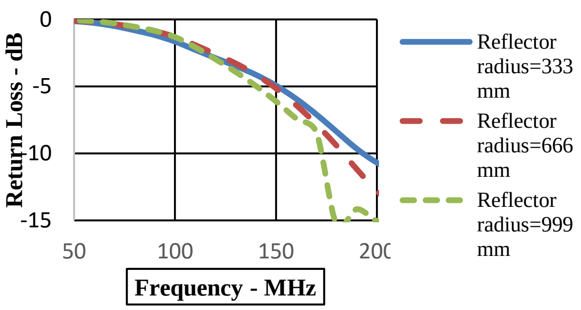

Fig. 7 Effect of Ground reflector radius on the return loss characteristics

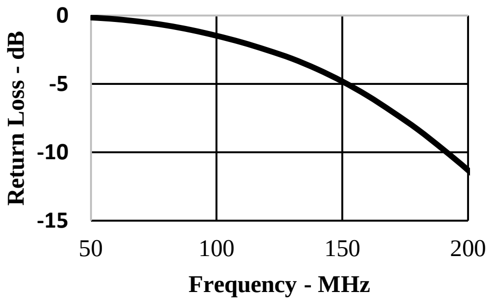

Fig. 8 Return loss characteristics when the ground reflector radius is made equal to 400 mm

Table.1 Optimized structural parameters of the spherical monopole antenna

Sl. No.	Descripton of the parameter	Optimized Value in wavelengths - λ_{min}
1.	Design wavelength - λ_{min}	1333 mm
2.	Radius of the sphere – r3	0.11
3.	Radius of the feeding conic section at the top – r2	0.0765
4.	Radius of the feeding conic section at the bottom – r1	0.0045
5.	Gap at the feeding section – g0	0.001
6.	Radius of the metallic reflector – a0	0.3
7.	Length of Monopole antenna	0.26

The simulated antenna structures is as shown in the Fig. 9

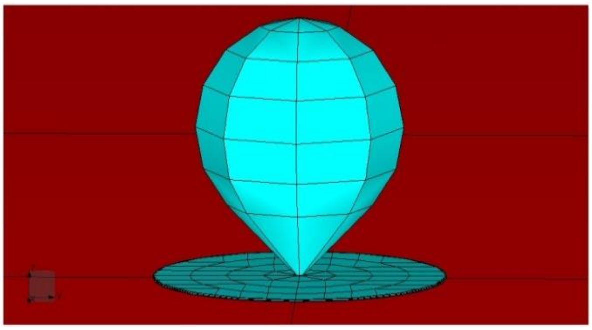

Fig.9.Simulated structure of the spherical Monopole antenna with a conical feeding section placed on the ground.

4. **Fabrication of the prototype**

The optimized spherical monopole antenna structure has two main sections: i) a conic section at the feeding point to properly match the antenna impedance with the receiver and ii) a spherical radiator. These two sections are independently fabricated and combined together finally to get the spherical monopole antenna.

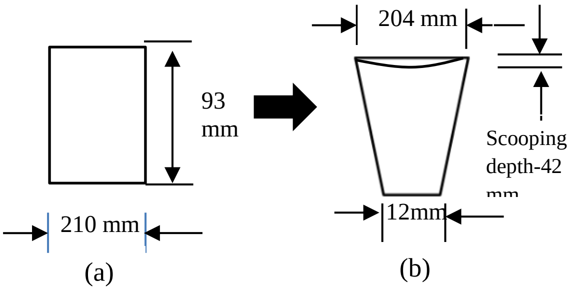

Fig. 10 Cylinder of appropriate dimension before turning into a cone in lathe (b) Cone after turning in a lathe. Scooping inside the cone is done at the top to ensure uniform of seating of the sphere on it.

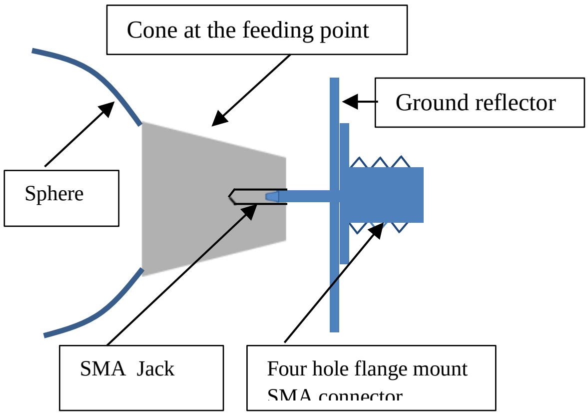

Fig. 12.Mechanism adopted to excite spherical monopole antenna

The conic section is fabricated by turning an aluminium cylinder in a lathe to the designed dimensions as shown in Fig. 10. The broader top surface of the cone is scooped to the desired depth to ensure perfect seating of the radiating spherical element on top of it.

The spherical radiator is produced by fabricating two hemispheres through the process of metal spinning and subsequently joining them. Metal spinning is a cold forming process of forming a blank metal sheet into the desired shape. In the process of metal spinning, a mandrel (metallic / wooden object) having the shape of the internal contour of the object to be formed, is fixed to the lathe. A blank circular metal sheet having diameter slightly greater than that of the sphere to be formed, is sandwiched between mandrel and follower on the tail stock spindle. When the mandrel, blank sheet and the follower are set in controlled rotation, the blank sheet is pressed against the mandrel using a spinning roller, making it to follow the shape of the desired part. After spinning, the spum metal is trimmed to get the right dimension and to blunt out the sharp edges. The two hemispheres fabricated in this process are joined together to make a complete sphere. The sphere subsequently is welded onto the input cone to get the monopole spherical antenna. The antenna is excited at the input conic section using SMA connector and jack assembly as shown in Fig. 12

The cone at its base is drilled to house the jack of the SMA connector. The centre conductor of the SMA connector fixed to the ground reflector is allowed to mate with the jack to establish the electrical contact between the antenna and the receiver electronics. The diameter of the centre conductor of SMA is turned till it had push-fit mating with the jack fitted to to the cone. The feeding technique adopted is robust, repeatable and long lasting. The styrofoam which is transparent to electromagnetic radiation was used to support the spherical radiating structure. The prototype of the antenna built is as shown in the Fig. 13.

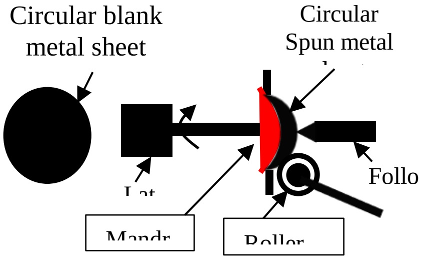

Fig. 11. Metal spinning process for fabricating a hemisphere

Fig.13. Prototype of the spherical monopole antenna. Styrofoam is used to support the antenna structure

5. Measurements of return loss

Return loss is one of the important performance indicators of the antenna indicating its efficiency of coupling the sky signal into the receiver electronics and vice versa. The coupling is primarily determined by the impedance mismatch between i) the space and the antenna and ii) antenna and the receiver electronics.

The measurement was made using Agilent N9915A-Field fox microwave hand held analyser. During the measurement, the antenna with a finite sized metallic reflector was kept on an imperfect ground. It was observed during the measurement that variation of ground properties had major impact on the impedance characteristics of the antenna. As a result, the resonance frequency, gain of the antenna and the spectral response showed significant variation under different ground conditions. In view of this, all our measurements were carried out under dry ground condition. The smoothness in the return loss response was measured by fitted it using a maximally smooth polynomial function and monitoring the residuals.

It was indeed a challenge to understand and overcome the problems encountered in the process of measurement. The residuals were found to vary as a function of time even though the experimental setup was kept unaltered. It was found that i) the instrument calibration used for the measurement was not stable during the period the measurement ii) repositioning of the long cable used for the interconnections resulted in the loss of calibration data and iii) reflection from surrounding objects introduced undesired features in the spectral response. All these problems were overcome by i) performing instrument calibration at regular intervals of time ii) measuring the return loss remotely without using RF cable and iii) keeping the measuring instrument as close to the antenna as possible. The return loss measured using this methodology is shown in Fig. 14 along with the simulation result. It is observed that the measurement matches well with the simulation within 0.2 dB. Smoothness of the spectral response is estimated by measuring the magnitude of the residuals obtained after fitting the measured data with a maximally smooth polynomial function. The residuals obtained is shown in the Fig. 15. The magnitude of the residuals indicates that the response is smooth to an extent of ± **5 parts in 10^4.** This implies that the background sky which is approximately 200 K bright at 150 MHz leaves behind spectral features of the order of ± 0.1 K in the output spectrum. For achieving smoothness of this magnitude, the radiating structure has been made to resonate at a frequency outside the band of observation (40-200 MHz) i.e around 230 MHz. As a result, it has good impedance match (>10 dB in return loss) at the band edge and progressively poorer match at lower frequencies. The poor antenna radiation efficiency at low frequencies is allowed in our design since the loss of sensitivity could be compensated by an increased sky brightness at those frequencies.

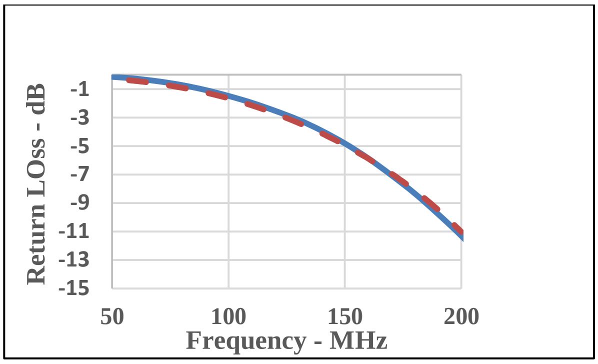

Fig. 14 Return loss characteristics of the spherical monopole antenna : Dotted line is the measurement and the solid line is simulation

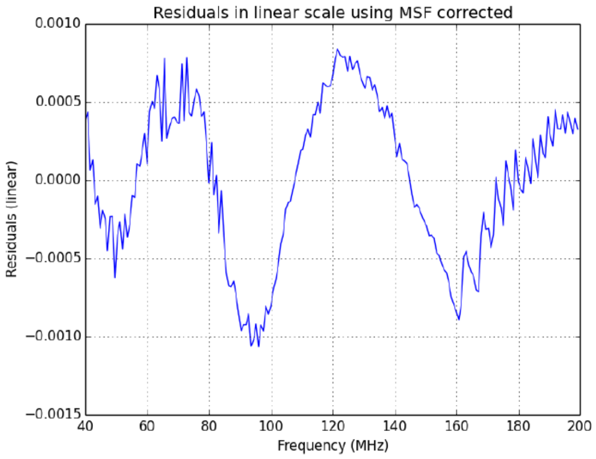

Fig. 15 Resuduals obtained after fitting the measured return loss data with maximally smooth function.

6. **Measurement of the Radiation Pattern**

Antenna radiation pattern was measured at ten discrete frequencies in the range 40-200 MHz. Their accurate measurement was challenging since the antenna is non-directive and sensitive to reflections from the surrounding objects. This required measurement volume to be free from reflecting objects like stray wires which offer larger cross-section particularly for low frequency signals and make the measurement highly inaccurate. In addition, the measurement volume also had to be unmanageably large (atleast 8^3 c.meter) for the measurement to have less near field effect.

In the experimental setup used for the measurement, the spherical monopole antenna under test was used as a receiver and a half wave dipole tuned at 200 MHz was used as the transmitter. The transmitter was kept above the ground at an appropriate height (2 to 8 m) to ensure far field distance between itself and the receiver at all frequencies of measurement. During the measurement, the transmitter was horizontally moved to different distances to measure the E-field pattern over a wide range of elevation angles.

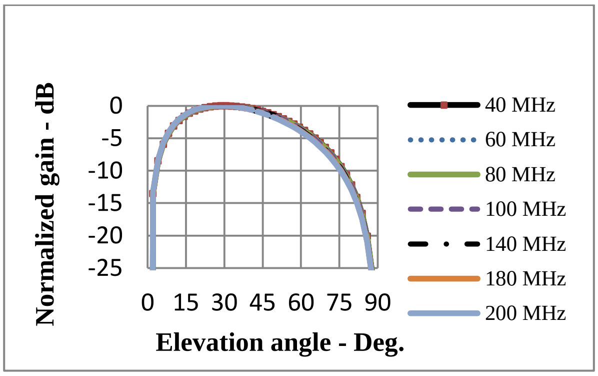

Fig. 16 Simulated radiation patterns of the spherical monopole antenna at discrete frequencies in the range 40 -200 MHz

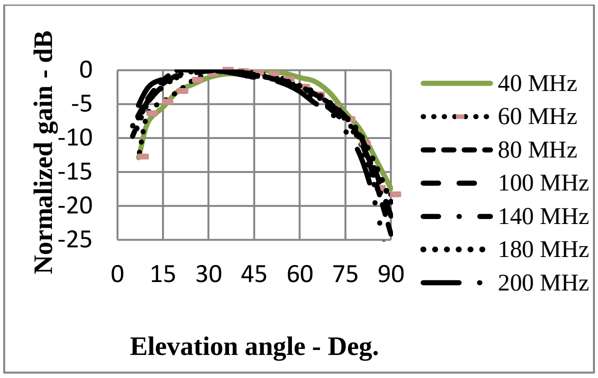

Fig. 17 Measured radiation patterns of the spherical monopole antenna at discrete frequencies in the range 40 - 200 MHz

A stable signal generator (Anapico Model No. ….) was connected to the transmitter to transmit CW signal in the frequency range 40 – 200 MHz at constant power level. The power received by the spherical monopole antenna was measured using the agilent Spectrum analyser (Model No. N9915A). The radiation patterns measured in E-plane at various frequencies are shown in Fig. 16 along with simulation results in Fig. 17. The measured patterns are observed to be frequency independent and match closely the simulation result with a maximum dispersion in the 3 dB beamwidth of about 10-12 %. The deviation in the peak positon observed at 40 MHz is attributed primarily to the near field effect and reflections from nearby objects. The antenna response is observed to have a NULL response both along horizon and at zenith indicating its insensitivity to interfering signals in those directions.

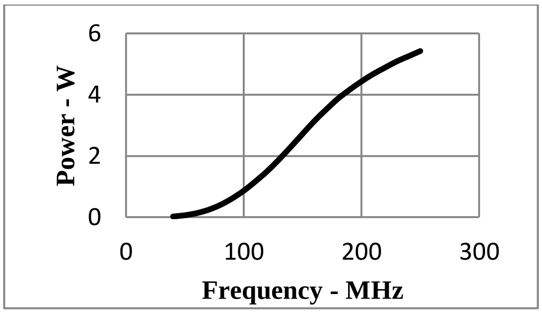

Fig. 18 Simulation result of the total power radiated by the spherical monopole antenna as a function of frequency when it is fed with an input power of 4*pi. The response is smooth as a function of frequency and free fromundesired spectral features. Poor response at low frequencies is because of antenna's high impedance mismatch at those frequencies.

The plot of total power radiated by the antenna as a function of frequency when it is fed with an input power of 4π is shown in Fig. 18. The response includes the mismatch effect of antenna impedance at its input. We observe that even though the radiation efficiency is poorer at lower frequencies, the overall response is smooth and is free from undesired spectral features. Thus in principle, the spherical monopole antenna could be used to detect features in the spectrum of CMB radiation.

7. Measurement of Gain

8. **Conclusion**

We have designed and developed an ultra wide band spectrally smooth spherical monopole antenna in the frequency range of 40 - 200 MHz. The impedance response of the antenna is smooth to a few parts in 10^4 and it with the simulation within 5%. The members in Gauribidanur Observatory for setting up the field experiments and help make measurements.

radiation patterns are frequency independent over the entire frequency band and have a max. dispersion of 10-12 % in their 3 dB beamdwidths. Since the antenna has smooth impedance and radiation responses, it can in principle be a candidate to detect the features in the spectrum of cosmic microwave background radiation.

Acknowledgments

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