Design of Microwave Power Transmission System for Lunar Rover

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1. Introduction

Data obtained by Clementine which is a lunar probe made by the U.S. Department of Defense suggest the presence of water ice at the south and north lunar pole. NASA's Moon probe Lunar Prospector (LP) data measured by LP's neutron spectrometer experiment support the contention that water ice reservoirs exists in the permanently shadowed craters at the lunar poles. [1] NASA estimated that there might be 10 to 300 million metric tons of water ice in these regions. However, these were indirect observations. To obtain more information of water ice, LP was intentionally impacted into a permanently shadowed lunar South Pole crater at the end of mission while Earth and space based telescope facilities were observing. The direct evidence has not been reported. A lunar rover is expected to be a candidate for the direct exploration mission.

Conventional photovoltaic cells are not feasible for the rovers in the permanently shadowed regions. Mission life is limited severely when the conventional battery storage system is only used. A nuclear power source is possible, but would tend to increase rover weight and cost. The use of power beamed from a base station or lunar synchronous orbits to the lunar rover has advantages. Several reports have described systems for transmitting power by microwave or laser beam from various locations to the lunar surface. [2]-[4]

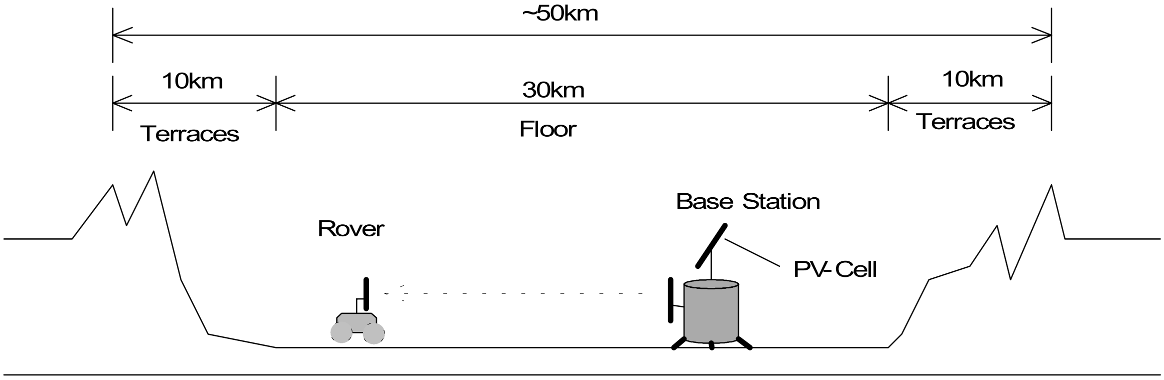

Fig.1 Microwave Power Beaming System from a Base Station to Lunar Rover

Since the microwave beam can be precisely steered electrically using a phased-array antenna, we chose the microwave power transmission system instead of the laser transmission system. In this paper, the microwave power transmission system from the base station to the lunar rover is proposed for the permanently shadowed area in the crater as shown in Fig.1.

2. System Requirements

LP's impact mission targeted the large relatively flat-bottomed crater with a low rim. Crater size is about 50 km in diameter.[1] Therefore, maximum transmission distance between the base station and the lunar rover is supposed 10 km for these specific missions. The requirements of this mission are as follows. The station locates at the sunlight region in the crater and generates the electrical power using solar arrays. The power is supplied to a transmitter for conversion to electromagnetic energy. From the output of the transmitter, energy can be transmitted directly through space to a receiver on the rover, which converts the electromagnetic energy back to electrical energy. A block diagram is shown in Fig. 2. The rectenna on the rover receives more than 100 W at the distance of 10 km. The rover survives in the station during the long lunar night. Furthermore, the key feature of this system is a transmission method, which utilizes two beam modes. One is a searching mode. The other is a power transmission mode. The beam shapes can be varied by controlling a phase of the antenna elements.

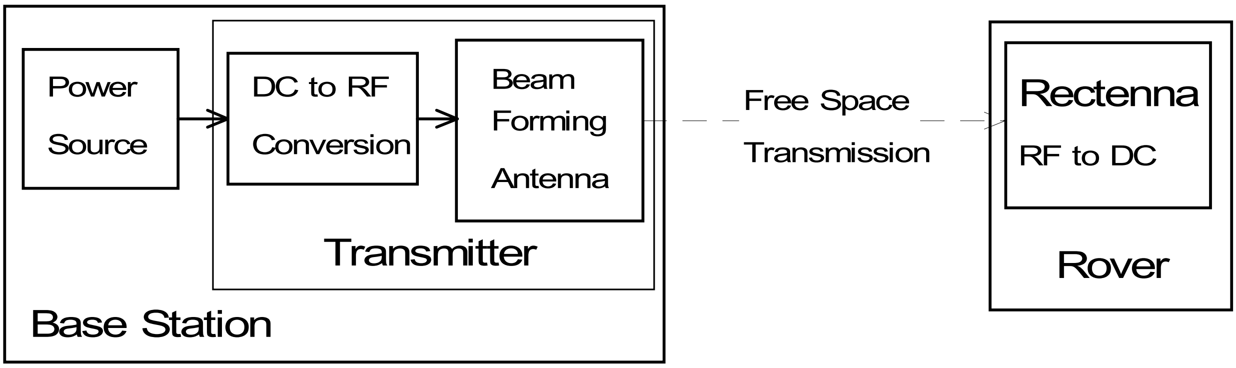

Fig.2 Block Diagram of the Beamed Microwave Power Transmission System

3. Design of the Microwave Transmitting System

For the microwave frequency ranges, the antenna/rectenna size is affected greatly as a function of frequency and transmission distance. Many studies for the application of power transmission on the earth or between earth and space were concentrated on 2.45 GHz. However, for the lunar or space-to-space applications the operating frequency can be increased to allow power transmission over much longer distances with the small antenna and rectenna.

The near field approximation used to size the transmitter and receiver area was

$$At \cdot Ar = \{-\log(1 - Pr/Pt)\} \cdot (Rc/f)^2 \qquad (1)$$

where R is distance (m), f is frequency (GHz), c is a velocity of light, At (m^2) and Ar (m^2) are transmitter and receiver areas and Pt (W) and Pr (W) are Transmitted and Received power, respectively. Using (1), transmitter and receiver areas for 63 % transmission efficiency are plotted as a function of frequencies at the transmission distance of 10 km in Fig. 3. By increasing the frequency, antenna sizes decrease and large mass saving results. However, fast wave devices such as gyrotron and FEL, which have some uncertainty as to availability for the space use, are needed above 100 GHz. Recently, helix-traveling wave tube (TWT) performance as measured in efficiency, life time and high-frequency has improved significantly. The microwave power module (MPM), which consists of a TWT and integrated power conditioner and solid-state amplifier, can be used for the microwave amplifier to provide 100 W over the 18-40 GHz frequency range. Efficiency is above 30 % up to 30 GHz. [5] Relative to alternate technologies, MPM offers a fourfold advantage in efficiency over solid-state power amplifier (SSPA) alone, and more than tenfold reduction in size relative to either a TWT amplifier and SSPA.

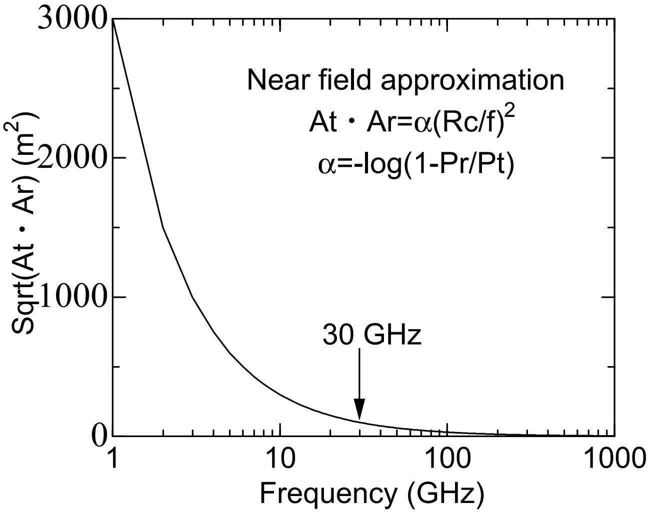

Fig.3 Transmitter/Receiver Size vs. Frequency
R=10 km, α=1.0

On the other hand, rectenna that receives and converts microwave power into dc power is a key element of the microwave power transmission system. The typical power transmission efficiency achieved is 85 % at 2.45 GHz. Recently, 35 GHz rectenna with efficiency of 60-70 % was reported.

The size of the transmitter/receiver determines the space transmission efficiency. Because good transmission efficiency was obtained by the adequate sizes of the antennas for the microwave systems under our mission requirements, the frequency of 30 GHz was chosen for the power transmission. The transmission efficiency is 9.4 % if the diameters of transmitter and

Table 1 Efficiencies of the transmission system

	Efficiency (%)
Transmitter	30
Free Space Transmission	9.4
Rectenna	60
Total	1.7

receiver antennas are selected 10 m and 4 m, respectively. Efficiencies of each subsystem are listed in table 1. Total efficiency is about 1.7 %. In order to provide more than 100 W to the lunar rover at the distance of 10 km, the solar array has to generate about 10 kW. Surface and weight of the solar array consisted of multi junction photovoltaic cells with conversion efficiency of 30 % are around 25 m^2 and 30 kg, respectively. The weights of the subsystems are listed in table 2.

Table 2 Weights of the subsystems

Base Station	Mass (kg)
Solar array	30
Transmitter	65
Antenna	150
*PMAD	40
Structure	20
Total	305
Rover	
Rectenna	20
*PMAD	10
Total	30

*PMAD : Power Management and Distribution

4. Conclusion

The power transmission system of the lunar rover by microwave beam is described in this paper. Use of the base station at the sunlight region makes it possible to carry out the scientific missions in the permanently shadowed regions.

References

[1]G.S.Hubbard,S.A.Cox,M.A.Smith,T.A.Dougherty and L.Chu-Thielbar, ”Lunar Prospector:Continuing Mission Results”, IAF-99-Q.4.02.

[2]M.D.Williams and E.J.Conway,”Space Laser Power Transmission System Studies”, NASA CP-2214, 1982.

[3]E.H.Fay,M.Stavnes and R.C.Cull,”Beam Power Options for the moon”, SPS91, pp.238-247.

[4]P.Koert and J.T.Cha,”Millimeter Wave Technology for Space Power Beaming”, IEEE Trans. Microwave Theory Tech., vol.40, no.6, pp.1251-1258, 1992.

[5]C.R.Smith,C.M.Armstrong and J.Duthie,”The Microwave Power Module:A Versatile RF Building Block for High-Power Transmitters”, Proceeding of the IEEE, vol.87, pp.717-737, 1999.