Non-planar log-periodic antenna feed for integration with a cryogenic microwave amplifier

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1 Introduction

The bandwidth of a microwave reflector telescope is limited by the size and figure accuracy of the mirror elements and by the feed which couples focused radiation to the receiver. A single or hybrid-mode feedhorn can efficiently illuminate a telescope aperture with low ohmic loss. Its gain varies quadratically with frequency, however, limiting its effective bandwidth to less than an octave. A log-periodic antenna (LP) can illuminate a telescope aperture over multi-octave bandwidths, but it has greater spillover and ohmic loss than a well-designed feedhorn. Moreover, in contrast to a horn, an LP is a large open structure, requiring a long twin-lead or coaxial cable to carry signals away from the near field region, before amplification. Loss in such cables can be greater than 1 dB, contributing more than 60 K to the receiver noise temperature. Also, motion with frequency of the phase center along the antenna axis may require a mechanical actuator to move the feed into focus for good illumination efficiency of the telescope.

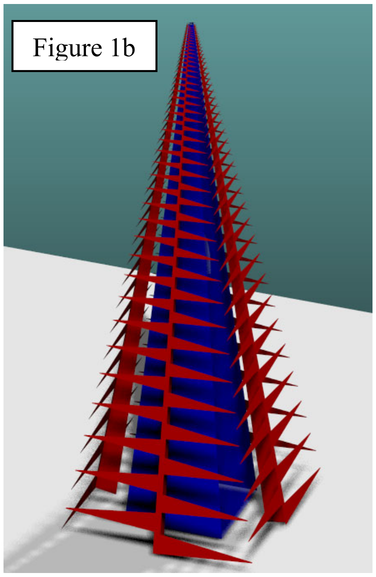
Figure 1a. Photograph of prototype log-periodic antenna feeds, LP1 (left) and LP2 (right). LP2 has a finline attached to the inner face of each arm. The finlines reduce cross-polarization coupling and ohmic loss.

This paper describes a non-planar log-periodic antenna feed to which cryogenic electronics can be attached without the need for a long, lossy section of transmission line (Figure 1a). With appropriate reflector optics to minimize defocusing with phase travel and baffles to redirect sidelobes onto the sky, this antenna offers a low noise, wideband alternative microwave feed for astronomical and SETI applications. It is currently being adapted for use on the Allen Telescope Array (Welch 1999; DeBoer *et al* 2002).

2 Antenna Design

While a planar log-periodic antenna has the advantage of being simple to fabricate, the 3dB contour of its main beam is elliptical. A two-arm non-planar LP, completely specified by two or more angles, a scale factor (τ), and two linear dimensions (D1 and D2), generates a circular beam if the angle of inclination between the two-arms (α) equals the angle of divergence (ψ) for the arm pattern [1]. In this geometry, opposing antenna arms are identical ``herringbone” shapes flipped 180° out of phase to yield a geometric sequence of switched dipoles. Signal terminals are attached to the small dipole end. In transmission mode, radiation is guided between the antenna arms to an active region where dipoles have the correct electric lengths (~$\lambda/2$) and phases to radiate in the backward direction, toward the smaller non-resonant elements. It is important to note that use of an LP geometry does not guarantee frequency independence. Antenna shapes must be properly selected and tuned to ensure low SWR and minimum variation of impedance and beamshape over a log-period of frequency. D1 and D2, linear dimensions of the smallest and largest dipole elements, determine the edges of the antenna passband.

Figure 1b



In an effort to design a microwave antenna feed with multioctave bandwidth, dual linear polarization, low ohmic loss, and low spillover, a variety of arm geometries with near unity scale factors were examined. An inclination angle between arms of 20° yields the best patterns with highest gain (10-11.5 dB), resulting in an antenna of practical size for 0.5-11 GHz. Design geometries were evaluated with Zeland Software IE3D, a full wave EM simulator. Initially, two-arm LP antennas with triangular, square, and trapezoidal tooth dipoles (τ = 0.940-0.985) were evaluated for gain, loss, and illumination efficiency. The illumination efficiency quoted in this paper is the total power falling within the 13 dB contour of the main beam. Thin wire sawtooth geometries have the highest illumination efficiency, 95%, but at the expense of more than 10% ohmic loss and input impedances greater than 300 ohms. Filled triangular teeth geometries show the most promise, with 93% illumination efficiency, impedances less than 250 ohms, and only 2-3% ohmic loss if a 3° wide central boom is added.

Emission from a filled triangular-tooth LP antenna is polarized along the direction of the dipoles. Dual quasi-linear polarization can be achieved by placing two LP antennas at right angles, resulting in a four-arm LP antenna with 90° rotational symmetry about the main beam axis. Unfortunately, the orthogonal antennas are electromagnetically coupled. Simulations show that fringe fields of the feeder-mode couple to currents directed along edges of the orthogonal booms, resulting in an elliptically polarized antenna. The forward-to-backward gain ratio, F/B, of a four-arm LP is less than 15 dB, much lower than expected for a two-arm LP (30 dB). The illumination efficiency of a four-arm LP is 88 %, roughly four percent lower than that of a two-arm LP.

In a conventional LP, terminals are connected to amplifiers via a long transmission line balun, attached to the boom, which pipes the RF signal out of the antenna near-field region to the low-field backlobe region. Loss in this cable can be considerable (~1dB), depending on the bandwidth of operation. To minimize system temperatures a low noise amplifier module must be close to the terminals. This can disrupt the radiation mode, if the module is attached in front, or the feeder mode, if it is placed between the antenna arms. The problem of amplifier placement is solved by introducing a square pyramidal metallic shield along the antenna axis. If a coaxial antenna and shield have a common vertex, the geometry of their combination is self-similar (Figure 1b). A shield opening angle of one half the antenna arm inclination angle ($\alpha/2$) preserves the frequency independence of the LP antenna, providing a convenient volume for placing electronics or a cryostat. For connecting amplifier and antenna, twin-lead transmission lines can be threaded out of the truncated tip of the shield. The presence of the shield enhances forward gain somewhat (g_{peak} ~ 12 dB) but also increases sidelobes, hence care must be taken to terminate spillover on the sky with the appropriate baffles in order to achieve low system temperatures.

3 Range Tests

A 1-10 GHz log-periodic antenna with shield (“LP1”) was constructed at the University of California Radio Astronomy Laboratory for range tests, conducted Nov. 2000 at Loral Corp., Mountain View, CA, and Aug. 2001 at NASA-JPL, Pasadena, CA. This antenna represents a design optimized by simulation for high gain (12 dB), low ohmic loss (3%), high illumination efficiency (83%), low SWR (< 1.4), and a convenient impedance (240 Ω) for matching to a low-noise MMIC amplifier. LP1 was connected to the range receiver through a low-loss taperline microstrip balun installed inside the shield. Shown in Figure 2 are 3 GHz copolarization range scans in the E-plane (thin solid line) and H-plane (thin dashed line) and their corresponding phases. Overlaid are the simulated E-plane profile (thick solid line) and the simulated H-plane profile (thick dashed line). Over the main beam, agreement between simulation and measurement is excellent. Within the 13 dB beam contour the phase distribution is flat to within a few degrees. Simulated and measured sidelobe levels agree, with the exception of small measured excesses at +/-60° in the H-plane profile, possibly due to range error. Shown in Figure 3 is the roll-angle-averaged beam profile of LP1 measured at frequency intervals of $\tau^{0.2}$ over a log period centered at 3 GHz. The profiles are remarkably similar, with the peak gain varying less than 0.75 dB. These measurements show that the antenna is indeed frequency independent. Roll-angle averaged 3 GHz cross-polarization scans are shown in Figure 6. The cross polarization coupling averaged within the 13 dB power contour of the beam is -15 dB.

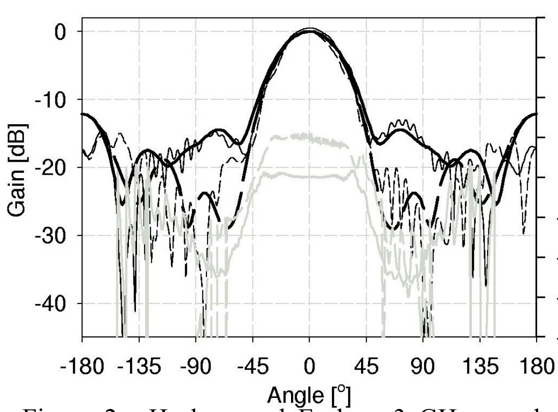


Figure 2. H-plane and E-plane 3 GHz copolarization range scans of LP1. Overlaid are model patterns and the measured H-plane and E-plane phase distributions.

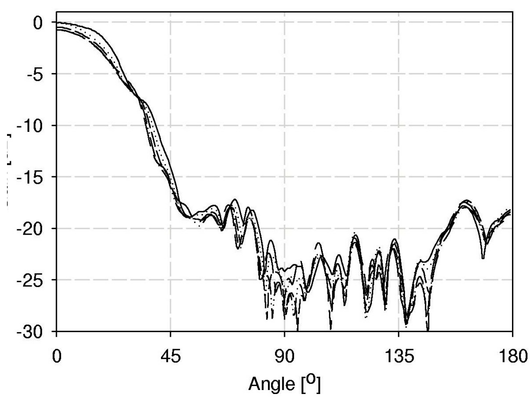


Figure 3. Roll-angle-averaged beam profiles of LP1 measured at frequency intervals of $\tau^{0.2}$ over a log-period centered at 3 GHz.

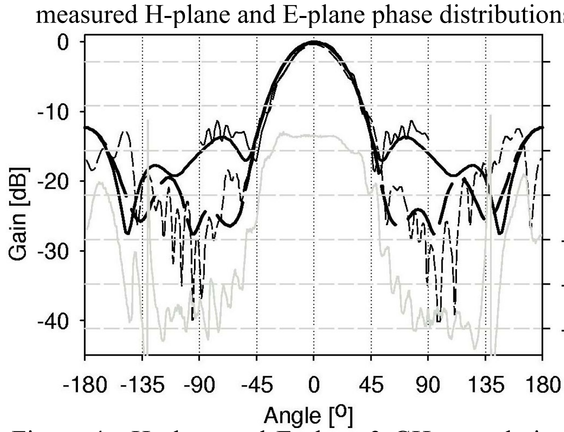


Figure 4. H-plane and E-plane 3 GHz copolarization range scans of LP2. Overlaid are model patterns and the measured H-plane phase distribution.

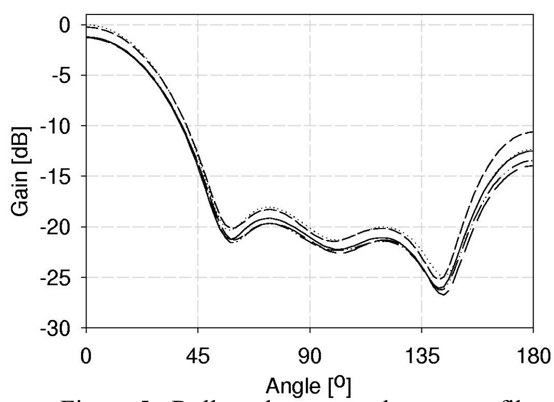


Figure 5. Roll-angle-averaged range profiles of LP2 computed at frequency intervals of $\tau^{0.2}$ over a log-period at 3 GHz.

In order to preserve the low ohmic loss and decrease the cross polarization coupling, the antenna design was modified by decreasing the boom width from 3.3° to 0.67° and adding a finline of opening angle 2.2° to the inside face of each antenna arm ("LP2"). The finline reduces fringe fields of the feeder mode. In addition, τ was changed from 0.975 to 0.960, thereby lowering reactive coupling of orthogonal arms. The combined changes reduce main beam cross polarization from -15 dB to -25 dB, a substantial improvement (Figure 6). The modified antenna LP2 was range tested Dec 2001 at NASA-JPL. The beam patterns measured and computed at 3 GHz, shown in Figure 4, are remarkably similar to those of LP1. This was initially unexpected, given their geometric differences. Only limited range data is currently available for LP2, but beam profiles simulated over a log-period in frequency, shown in Figure 5, demonstrate that LP2 is also frequency independent.

4 Conclusion

LP1 and LP2 are both promising broadband microwave feeds for integration with cryogenic low-noise amplifiers. For astronomical telescopes, LP2 should be somewhat preferred given its higher polarization purity. LP1 is easier to fabricate if elliptical polarization is tolerable. In current efforts to adapt this feed for use on the Allen Telescope Array, compact cryogenics [4] and low-noise InP MMIC amplifiers are under development at University of California, Berkeley, NIST-Boulder, and NASA-JPL. [5] Noise characteristics of LP2 connected to a 4-stage distributed amplifier were estimated using the Optotek linear simulation software package MMICAD. The results are shown in Figure 7, which includes the predicted gain and noise temperature of a plausible cryogenic amplifier and the system temperature of the feed linked to the amplifier. It is assumed that spillover onto the ground has a small effect, with the main beam and stray rays redirected onto a 3 K sky. The S-matrix of the antenna was derived from IE3D simulations for a 0.5-11 GHz version of LP2. The four-stage distributed amplifier design was optimized for low noise (~12 K) from 0.5 – 9.0 GHz with the Pospieszalski field effect transistor model, evaluated with electrical parameters for InP and T_{amb} = 80 K, but with a modest gain of 15 dB. Predicted LP2/MMIC system temperatures were 22 K at midband and less than 50 K at the band edges. These are comparable to system temperatures achieved with narrowband microwave feedhorns currently installed on the VLA[6]. It is expected that the ATA implementation will achieve better performance over most of the band with an optimized amplifier.

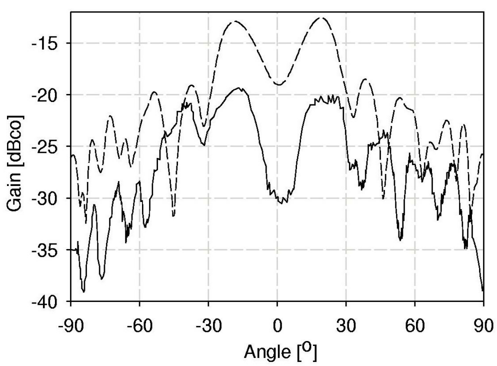


Figure 6. Cross-polarization range scans of LP1 and LP2, averaged for E- and H-plane.

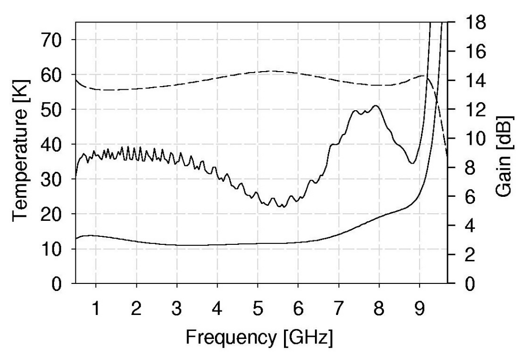


Figure 7. Predicted system temperature of a distributed 4-stage InP MMIC amplifier at T_{amb} = 80 K attached to LP2 (center line). The lower solid line is the amplifier noise contribution and the dash line the amplifier gain.

5 References

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