Yagi–Uda Array as a Surface-Wave Launcher for Dielectric Image Lines

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Abstract—A Yagi–Uda array of monopoles is embedded in the dielectric of a dielectric image line, with the driven element fed from coaxial cable below the metallic ground plane, in order to launch the dipole-mode surface wave. The launching efficiency is a function of the array length and is relatively independent of the transverse dimension. With a six-element array, a launching efficiency of 62 percent has been achieved over an 18-percent bandwidth at 2.2 GHz. A design procedure for such arrays is described and experimental verification is given.

INTRODUCTION

THE surface wave guide as a continuously accessible guided-wave structure has received much attention recently with particular emphasis on its use for guided communications in railway [1], [2] and other guided ground-transport systems. Gallawa *et al.* [3] have reported extensive theoretical and experimental investigations of the performance of a Goubau line for this application. By use of a dielectric-loaded conical horn they achieved a launching efficiency from coaxial cable as high as −0.3 dB. Although their horn was an improvement on earlier designs, its performance still depended upon its transverse dimension to a major extent, which could be a disadvantage in a long line with periodic coupling into repeaters, and a consequent number of transversely extending horns. For use on a coupling line on a moving vehicle the horn also presents an aerodynamically bad shape: it is necessary to place it in a recess with a consequent undesirable bend in the Goubau line on the vehicle.

These considerations led to the investigation by Dewar and Beal [4] of the use of a longitudinal array of 360° circumferential slots in the outer conductor of a coaxial cable to launch a TM_0 surface wave on a Goubau line formed on the outside of that cable. In this way, the efficiency of the launcher was made dependent upon its longitudinal, rather than its transverse, dimension and the continuity of the Goubau line was only slightly disturbed.

Reported difficulties [3] in supporting the Goubau line without disturbing its fields have led to a reappraisal of the dielectric image line [Fig. 1(a)], as reported by King [5], which includes its own rigid support in the form of a metallic ground plane. With dimensions and materials of practical realizability, a useful line can be made having both a desired transverse field extent and a low longitudinal attenuation.

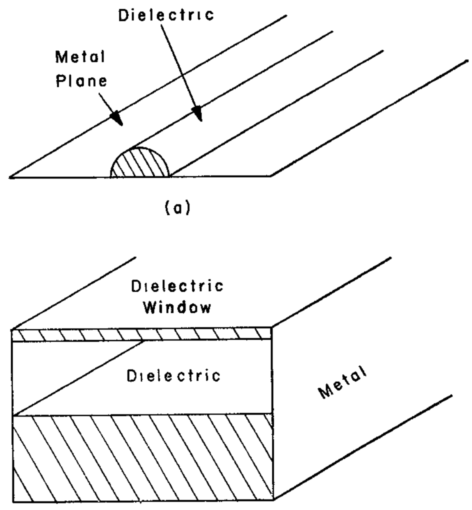

Fig. 1. Forms of the dielectric image line. (a) Basic form. (b) Derived form; trough line.

This paper describes the design and experimental investigation of a novel method of launching the dominant HE_{11}, or dipole, mode on a dielectric image line by means of a longitudinal Yagi–Uda monopole array embedded in the dielectric of the image line. The driven element of this parasitic array is fed directly from a coaxial cable mounted behind the ground plane, thus leaving the working surface of the line essentially undisturbed. This new launcher is also appropriate to use on novel guiding structures such as a possible trough line [Fig. 1(b)], whose essential feature is that the sensitive dielectric–air interface is protected from the environment by a dielectric window, analogous to a radome. This type of guiding structure could also be buried in the surface of a highway or monorail structure to provide continuous guided control and communication.

THE SURFACE-WAVE LAUNCHER

It is useful to review the properties of the HE_{11} mode on the dielectric image line. Fig. 2 is a graph of relative phase velocity versus the ratio $2a/\lambda_0$ for the dipole mode (a is the cross-sectional radius of the dielectric of the image line). This graph was plotted from a numerical solution of the eigenvalue equation derived by Collin

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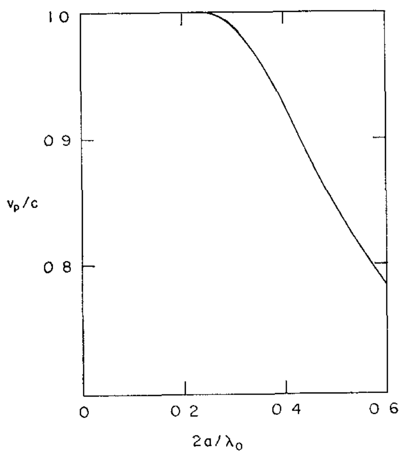

Fig. 2. Relative phase velocity versus $2a/\lambda_0$.

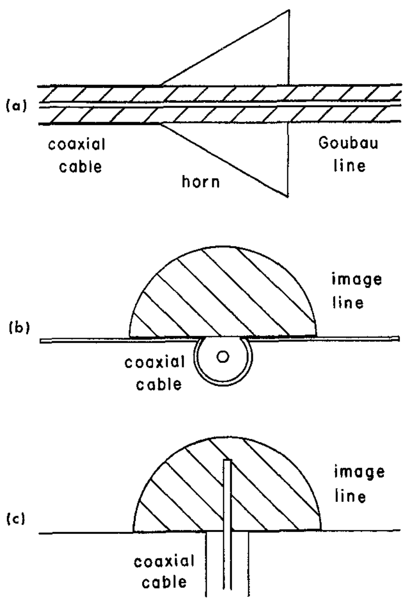

Fig. 3. Surface-wave launchers. (a) Horn. (b) Coaxial slots. (c) Monopole.

[6], and is interesting to the extent that it shows that the dipole mode has a practical cutoff frequency given by $2a/\lambda_0 \simeq 0.25$. If a is chosen to be 0.025 m, this implies that the image line ceases to be a practical slow wave structure at frequencies below 1.5 GHz. King and Schlesinger [7] have made numerical calculations of attenuation for the dipole mode, which indicate that both dielectric and conduction losses increase rapidly with the ratio $2a/\lambda_0$. This, together with this "cutoff" frequency of the HE_{11} mode, determines the useful range of frequency for the image line.

The first attempt to make a longitudinal-array launcher for the dielectric image line was an adaptation of the slot array of Dewar and Beal [4]. An array of partial circumferential slots was formed in the outer conductor of the coaxial cable, which then fed a similar array of slots in the image plane [Fig. 3(b)]. For all these early experimental slot arrays it was found to be impossible to couple any measurable power from the coaxial line to the HE_{11} image line mode. It appeared that these partial circumferential slots in the 0.5-in diameter coaxial cable did not constitute a significant discontinuity in the frequency band of interest (1 to 2 GHz).

Duhamel and Duncan [8] have previously reported a monopole launcher for surface waves on a dielectric image line, a form inherently suited to a direct feed from a coaxial cable behind the ground plane [Fig. 3(c)]. The bidirectionality and low efficiency of the single monopole are not satisfactory, however, and the need for some kind of array is obvious. An all-driven array of monopoles would probably lead to the best performance, but at the expense of a complicated design procedure and a difficult process of mechanical construction. A much simpler approach was adopted by use of a parasitic array having only one driven monopole element, the design procedure being an adaptation of that reported by Ehrenspeck and Poehler [9] for the monopole version of the Yagi–Uda antenna.

Experimental Design

In conventional Yagi design, the element heights and spacings are decided by resonance and phase-delay effects, respectively, if the gain is to be a maximum in the end-fire direction. When a parasitic array is embedded in a dielectric for use as a surface-wave launcher, several effects may be anticipated.

1) The resonant heights of the monopole elements are shortened and the input impedance is decreased.

2) The phase delay between elements is increased if the spacing is not changed.

3) The dielectric–air interface in the near field of the antenna modifies the radiation pattern of the array. As a first approximation, the resonant height of a single monopole embedded in the image line dielectric was determined experimentally, and this height was used to define an effective permittivity ϵ_r of the combined dielectric and air medium. A new wavelength λ was then defined as $\lambda_0\sqrt{\epsilon_r}$, and the element heights were determined as fractions of λ in the same way that the heights are determined from λ_0 in conventional Yagi–Uda antenna design. Since it was desired that the power propagated along the array would be in the form of the dipole-mode surface wave, with wavelength λ_{sw}, the spacing between elements was made $\lambda_{sw}/4$. To increase the input impedance of the array, the driven element was made into a folded monopole with its two halves aligned with the other elements of the array.

The details of the experimental models tested may be summarized as follows.

Dielectric Image Line

1) Design frequency: 2.2 GHz.

2) Ground plane: 1/8 in aluminum sheet, 0.45 m×6 m, with conductivity, $\sigma_c = 3.12 \times 10^7$ mho/m.

3) Dielectric: 0.025-m radius polystyrene semicylinder with a dissipation factor of 0.0003 at 2.2 GHz and relative permittivity $\epsilon_r = 2.56$.

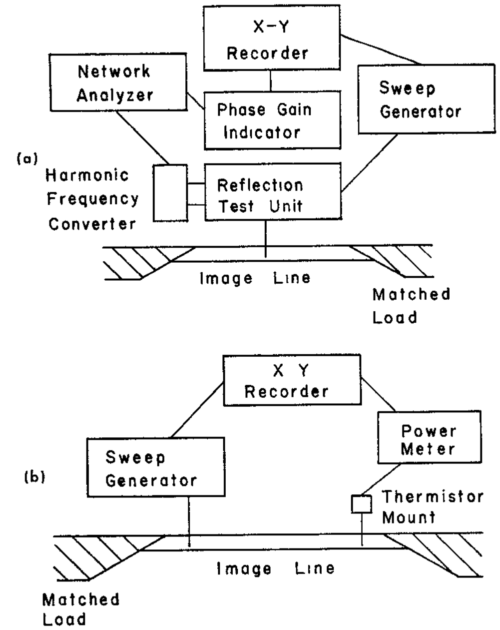

Fig. 4. Block diagram of the apparatus. (a) Reflection measurements. (b) Transmission measurements. Sweep generator: Hewlett-Packard 8690A; reflection test unit: HP-8742A; network analyzer: HP-8410A; power meter: HP-432A.

4) Surface-wave-absorbing loads: carbon impregnated polyfoam.

Monopole

1) Wire diameter: 0.0041 m.
2) Resonant height at 2.2 GHz: 0.0195 m.
3) Spacing between the two halves of the folded monopole: 0.0063 m.
4) Effective relative permittivity: $\epsilon_r = 2.25$.
5) Effective wavelength: $\lambda = 0.091$ m.

Yagi–Uda Array

1) Driven element height: 0.0195 m.
2) Reflector height: 0.0206 m.
3) Director height (h_D): 0.0152 m.
4) Element spacing: 0.0325 m.

Results

A schematic diagram of the apparatus used for the experimental measurements is shown in Fig. 4. To determine the performance of a launcher it is necessary to construct two identical launchers: one to couple power from the signal generator to the image line, the other to couple power from the surface-wave field excited by the first launcher to a measuring device. The launchers may be represented as four-port networks, as in Fig. 5. Port 1 is the input to the launcher from the signal generator, ports 2 and 3 are the output terminals for the forward and reverse components of surface-wave power, and port 4 is the output terminal for the radiated power. By use of reciprocity and the identical nature of the two launchers, it is possible to determine the magnitudes of S_{11}, S_{21}, and S_{31} by measuring the normalized voltages a_1, b_1, and b_5. The magnitude of S_{41} is then related by the law

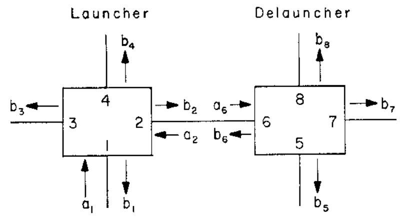

Fig. 5. Four-port network representation of surface-wave launchers. $b_1 = S_{11}a_1 + S_{12}a_2$; $b_2 = S_{21}a_1 + S_{22}a_2$; $b_6 = S_{66}a_6$; $a_6 = b_2$; $b_6 = a_2$; $a_2 = S_{66}b_2$; $b_5 = S_{56}b_2$.

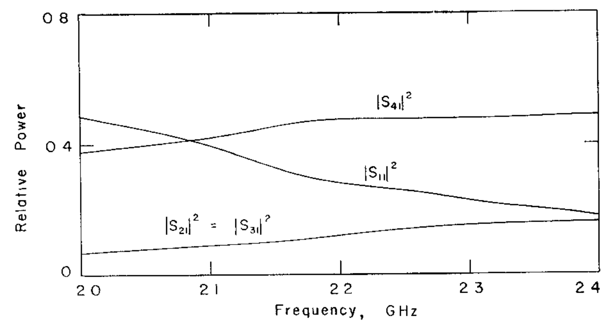

Fig. 6. Network description of a monopole launcher.

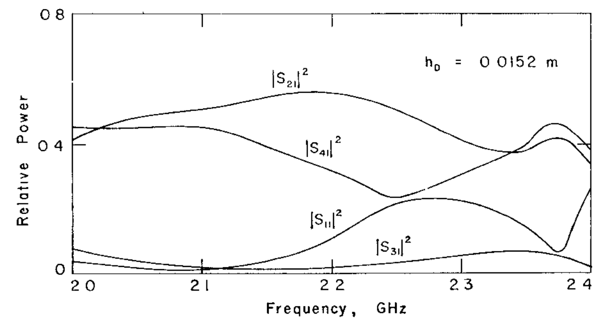

Fig. 7. Six-element array launcher.

of conservation of average power:

$$|S_{11}|^2 + |S_{21}|^2 + |S_{31}|^2 + |S_{41}|^2 = 1.$$

Thus the performance of a launcher may be completely described, since all four components of the power that it excites are known.

The monopole antenna was first analyzed in this fashion for comparison with the Yagi–Uda array and the results are shown in Fig. 6. The dominant term is the radiated power $|S_{41}|^2$. It is precisely this term which must be reduced to a negligible value, since one major advantage of communication by means of a surface-wave transmission line over radio communication is the former's nonradiating characteristic. If the launcher produced such a large amount of radiation, this advantage would be destroyed.

The performance of a six-element Yagi–Uda array is shown in Fig. 7. Modification of the feed element to a folded monopole has increased the input impedance of the launcher and reduced S_{11}, while the addition of a reflector has reduced S_{31} to an almost negligible value. The latter reduction is important, since two launchers typically would be placed back-to-back at intervals

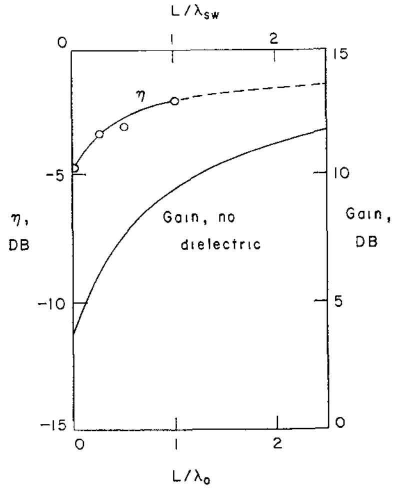

Fig. 8. Launching efficiency versus array length showing experimental curve of η and the gain of a Yagi–Uda array in free space [9].

along the surface-wave transmission line to couple power to and from repeaters. With such a low reverse component of surface-wave power excited by the launchers, an absorbing load would not be required to isolate them.

It should be noted that all the scattering parameters were deduced from measurements of S_{51} and S_{11} with the assumption that the attenuation introduced by the length of image line between the launchers was negligible. In theory, this was a valid assumption [7], but in fact there was an appreciable amount of attenuation due to mechanical irregularities in the image line used. This had the effect of decreasing the measured values of S_{21} and S_{31} and of increasing the value of S_{41}. Thus although S_{41} appears to be exceptionally large, it could be reduced somewhat simply by machining to closer tolerances and using better quality materials. One fina point of interest in Fig. 7 is the minor null in $|S_{11}|$ at 2.38 GHz. The low VSWR at this point may be attributed to the mutual coupling effect of the detuned elements of the launcher.

Fig. 8 summarizes the experimental results. The launching efficiency η has been defined by

$$\eta = |S_{21}|^2/(1 - |S_{11}|^2)$$

since S_{11} can be reduced to a small value by changing the feed element of the array to a folded monopole and can be eliminated by impedance matching. The curve η has been plotted against the normalized array length L/λ_{sw} where λ_{sw} is the wavelength of the dipole mode surface wave. Errors in the measurements of η are relatively insignificant in comparison with those introduced by imperfections in the construction of the experimental models. The first point, at $L=0$, is the launching efficiency of the combination of the feed element with a reflector, in decibels, below a launching efficiency of 100 percent. The second curve is from the work by Ehrenspeck and Poehler [9] and is the end-fire gain of a Yagi–Uda monopole array in free space. The 0-dB gain level corresponds to the power measured in the end-fire direction from a single monopole. Since this curve is approximately asymptotic to a 15-dB gain, the 0-dB gain level was made to coincide with the −15-dB launching efficiency level so that it could provide a comparison with the experimental curve η.

Conclusions

A Yagi–Uda monopole array embedded in the dielectric of a dielectric image line has been shown to provide a useful alternative to the horn [Fig. 3(a)] for launching surface waves on such a structure. A six-element array has been shown to have an observed surface-wave launching efficiency of 62 percent at 2.2 GHz, with an 18-percent bandwidth between the −3-dB points. A design procedure for such arrays has been given and could be extended to longer arrays.

The major advantages of this launcher are as follows.

1) Launching efficiency is primarily a function of the length of the array and not of the transverse dimension, which is no greater than that of the dielectric itself, at the frequency used for these tests.

2) The construction is simple, consisting of wire elements rigidly enclosed in the dielectric.

3) The form is inherently suited to direct excitation from a conventional coaxial cable mounted behind the ground plane.

4) It is immediately appropriate to use as a launcher in unorthodox guiding structures, such as the dielectric-clad trough guide, that might be well suited to use for communications in guided ground-transport systems.

Further work is planned towards the goal of rivaling the launching efficiency of horn launchers by use of longer arrays and by continued refinement of the design procedure.

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