A 50:1 BANDWIDTH COST-EFFECTIVE COUPLER WITH SLICED COAXIAL CABLE

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ABSTRACT

A 20 dB 50:1 bandwidth, extremely low-cost coupler with sliced coaxial cable is reported in this paper. The proposed coupler consists of two shaped coaxial cables with adequate sliced linear-tapered cuts and soldered together. It has excellent performance in terms of low VSWR, good isolation, excellent EMI shielding, ultrawide coupling bandwidth, and high power handling capability. Good agreement between measurements and calculations on one hand shows the excellent performance of the coupler, and on the other hand validates the design procedure.

INTRODUCTION

This paper presents analysis, computer-aided design, and experimental verifications of a new non-uniform coupling line type of extremely low-cost, high performance couplers with ultra-wide bandwidth using coaxial cables. The proposed coupler consists of two curved coaxial lines with linear-tapered sliced cuts and soldered together as shown in Fig.1. The coupling is made through the cut window. By proper control of the cut depth and the coupling length with mechanical milling, different coupling coefficients and bandwidth can be readily achieved. Due to the TEM mode coupling nature, this kind of coupler has excellent performance in terms of high directivity, very low VSWR, good isolation, excellent EMI shielding, and ultra wide coupling bandwidth. Compared with stripline and planar transmission couplers, the coaxial cable coupler has significant higher power handling capability, especially suitable for RF and microwave high power transmitters applications, such as satellite transmitters and base stations of wireless communications systems. The extremely low cost of the coupler is the result of inexpensiveness of commercially available semi-rigid cable, ease of fabrication, and elimination of mechanical housing. In the fallowing, we first present a set of accurate closed-form formulas for the even and odd mode characteristic impedances of the coupled-line made of two sliced coaxial cables. And then present the design and measurement results of an ultra-wide band coupler.

SLICED CABLE COUPLED LINE

As well-known, electrical properties of the coupler with TEM-mode coupled line can be described in terms of even and odd mode impedances. Various numerical techniques can be used to determine the accurate characteristic impedance of the TEM coupled line. However, they are too time-consuming for direct application in circuit design and optimization. Closed-form analytical models are strongly desired for industrial applications.

The cross-section of coupled line made of two identical sliced coaxial cables is shown in Fig.2. The coaxial cable has an inner conductor of radius a and an outer conductor with inner surface radius of b. A dielectric material (permittivity: ε_r) fills the inside of the cable. A portion of each cable is milled out to form the coupled line. The cut depth is represented by h in the cross-section.

Based on the analysis of finite element technique and curve fitting technique, it is found that the even and odd mode impedances (Z_{oe}, Z_{oo}) of the coupled line can be expressed as [1],

$$Z_{oe}(u) = Z_0\left[1 + k_0 u^{k_1} + k_2 \sin(6u^2)\right]$$

$$Z_{oo}(u) = Z_0\left[(1-u^4)^k - 1.25(12-10u)^{-6} - 0.01k\sin(6u^2)\right]$$

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where Z_0 is the characteristic impedance of the coaxial cable given by

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{b}{a}\right)$$

and

$$u = \frac{\theta}{\theta_0} = \frac{\operatorname{acos}\left(\frac{h}{b}\right)}{\operatorname{acos}\left(\frac{a}{b}\right)}$$

with

$$k_0 = 0.1623 + 0.371r - 0.0696r^2$$

$$k_1 = 1.15\,(r+1)$$

$$k_2 = 0.028\tanh\left(\frac{r^3}{5}\right)$$

$$k = 0.45 - 0.01\left|\left(\frac{3.3}{e^r}\right)^3 - 1\right|$$

$$r = \ln\left(\frac{b}{a}\right)$$

The valid range of the even and odd impedance formulas is $0 \le u \le 0.99$ for coaxial cables with outer-inner conductor radius ratio of $1.4 \le b/a \le 10$. The accuracy is better than 1%.

LINEAR-TAPERED COUPLER ANALYSIS

The proposed sliced broadband coaxial cable coupler, as shown in Fig.1, has a linear-tapered coupled line configuration consisting of two same tapered lines (length=L) with each of them zero sliced cut depth at one end and h_e at another end.

Essentially, the tapered line coupler by sliced coaxial cables belongs to the category of nonuniform TEM line couplers. Due to the symmetry of the structure along the cut plane, the coupler can be seen as a pair of even and odd mode tapered transmission lines followed by an abrupt return to the port impedance level. The tapered line behaves as an impedance transformer which transforms the port characteristic impedance present at one end of the coupler to a higher impedance level in even mode and to a lower level in odd mode. The reflection of energy from the discontinuity provides the requisite coupling in the high pass manner [2].

As the even and odd modes of the linear-tapered coaxial cable coupler can be treated separately, the four-port analysis can be simplified. The two-port nonuniform lines can be treated approximately with a large number of short equal-length segments whose values of impedance follow the taper of the nonuniform line. Each segment can be modeled as a piece of uniform transmission line with the impedance value present at the center of each segment. The analysis is then performed by evaluating the cascade *ABCD* matrix of the lines as a function of frequencies[3]. The response converges to that of the smooth tapered couplers as the number of line segments increases.

Once the two-port S-matrices of the even and odd mode of the coupler are calculated, the four-port S matrix of the tapered-line coupler can be readily obtained with the technique given by [4]. A computer code has been developed for the analysis and design of the linear-tapered broadband couplers with sliced coaxial cable.

The mean value of the coupling coefficient of the tapered nonuniform line coupler with cut coaxial cables is determined by the end of the cut followed by the abrupt return to the cable characteristic impedance Z_0. For the semi-rigid PTFE filled 50 Ω coaxial cable (such as UT-85, UT-141, UT-250, etc.), Fig.3 shows the mean values of the coupling coefficients as the function of the normalized cut depth h/a. It is clear for the cut value of h/a=1.1, the coupling is -10 dB, which could be the maximum coupling realized with this type of 50 Ω coaxial cable. Within the cut range of $1.3<h/a<2.3$, -13 to -25 dB coupling can be achieved. Due to the high-pass nature of this linear-tapered line coupler, the low-frequency cutoff of the coupling is determined by coupling length L. Fig.4 gives the low-frequency cutoff as a function of coupling length L for different cut depth. It is seen that the cutoff strongly depends on the coupling length, the longer the coupling length is, the lower the cutoff. For a 150 mm coupling length, the cutoff is around 300 MHz.

As mentioned before, this type of non-uniform transformer-line directional couplers needs an abrupt return to the port impedance from the deepest cut in order to keep the high pass behavior. For practical realization, however, it is impossible to obtain this abrupt junction by milling the coaxial cable. A curved section is a must for the transition.

This results in the drop of coupling at higher frequencies. Assuming r is the radius of the curved section from the deepest cut to coaxial cable, the effect of the transition on the coupler performance can be simulated with the cascaded technique similar to that of the linear-tapered section described previously. Fig.5 shows the coupling coefficients as a function of frequency for different cut values and radius of the curved section (UT-250 in this calculation). The three sets of curves correspond to h/a=1.1, 1.4, and 1.8, respectively. For each set, the four curves are the responses of the values r=0mm, 5 mm, 10 mm, and 20 mm from above to below, respectively. For lower frequencies ($L/\lambda<2$), the effect of the curve is negligible. For higher frequencies, however, the effect becomes significant: the smoother the transition is (larger r value), the larger drop of the coupling coefficient from the mean value will be. This effect was observed from our measurement. Therefore, special measure should be taken to compensate this effect so as to get better performance at higher frequencies.

DESIGN EXAMPLE

A 20-dB broadband coupler was fabricated and measured. The cable used is UT-250 with a=0.815 mm, b=2.655 mm, and the cut depth h/a=1.8. Fig.1 shows the photograph of the coupler. The linear-tapered cuts have a coupling length of 14.0 cm. The curved section has a radius of r=6 mm as the transition from the deepest cut to the 50 Ω coaxial cable. As the abrupt coupling change is very important, a capacitive tuning tab is introduced at the junction to compensate the curved transition. Fig.6 illustrates the measured and calculated coupling coefficients with and without tuning tab. The theoretical curves are calculated from r=0 and 6 mm, respectively. One can see the agreement between the measurement and simulation is very good, validating our analysis technique. Without the tuning tab, the coupling coefficient drops 5 dB around 16 GHz. The improvement of the coupling coefficient on the higher frequencies is significant by using the tuning tab, the frequency response become very flat as predicted by the theory. For a flatness of ±1 dB, a coupling bandwidth from 0.32-16.6 GHz, which corresponds to 50:1 bandwidth ratio, is realized, indicating the ultra-wideband behavior.

CONCLUSIONS

A new type of ultra-wide band, extremely low-cost, high-performance couplers using sliced coaxial cables is presented in this paper. A set of accurate closed-form formulas is first given for the even and odd mode characteristic impedances of the coupled-line made of two sliced coaxial cables, with an accuracy of better than 1% for a wide-range of cut depth in order to facilitate the industrial applications of the coupled lines. Secondly, based on the theoretical investigations of the proposed coupler, an ultra-wideband coupler with 50:1 bandwidth is realized. A technique is developed to compensate the drop-off of coupling in higher frequencies due to the curved transition. Good agreement between measurements and calculations on one hand shows the excellent performance of the coupler, and on the other hand validates the design procedure.

ACKNOWLEDGMENT

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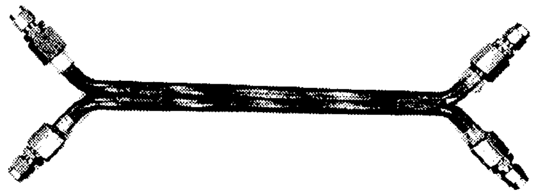

Fig.1. Nonuniform-line (linear-tapered) directional couplers with sliced coaxial cable.

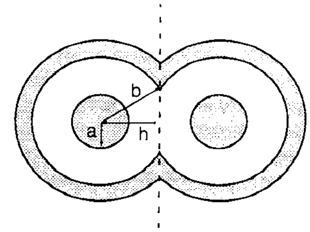

Fig.2. Cross-section of the coupled line with sliced coaxial cable.

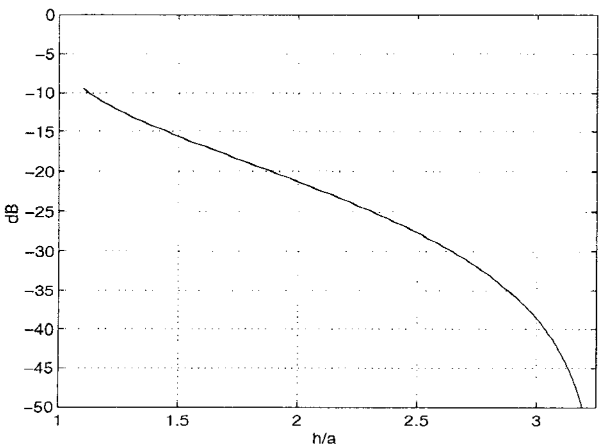

Fig.3. Mean value of coupling coefficient of linear-tapered nonuniform line coupler with 50 Ω coaxial cables as function of cut depth.

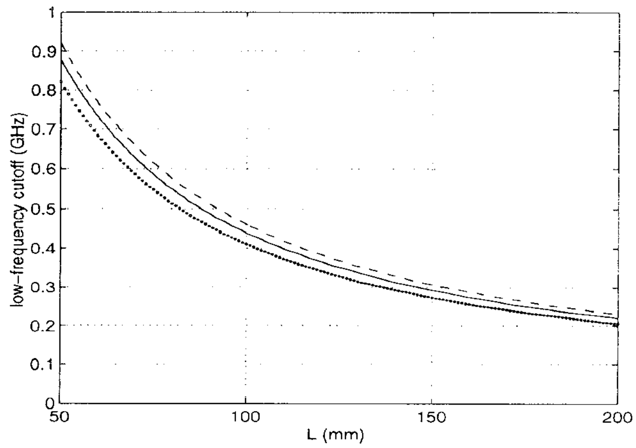

Fig.4. Low-frequency cutoff as the function of coupling length L for different cut depth.
- - -: h/a=1.1, ---: h/a=1.4, ...: h/a=1.8

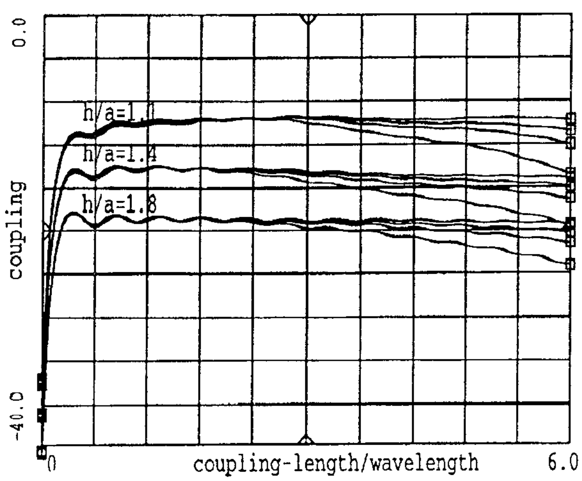

Fig.5. Coupling coefficients as the function of frequency for different cut values and radius of the curved section (UT-250 cable used in this calculation). Each set of curves corresponds to r=0 mm, 5 mm, 10 mm, and 20 mm from above to below.

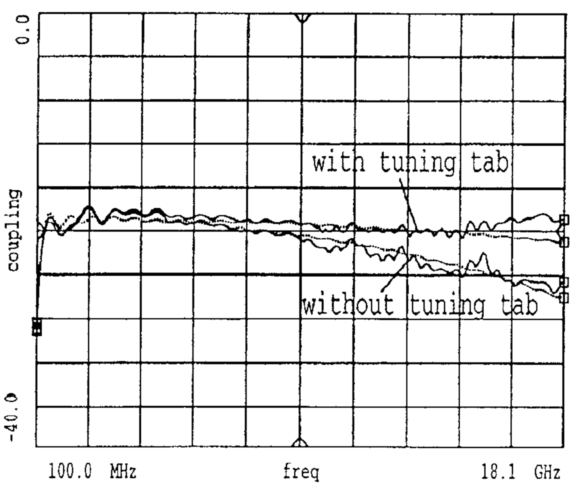

Fig.6. Measured and calculated coupling coefficient with and without tuning tab.
---: measurement, ...: calculation.