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A Four-Decade Bandwidth Hybrid Coupler

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Abstract

A hybrid coupler is a reciprocal radio-frequency building block with four ports. Signal power applied to any port is equally divided between the two adjacent ports, while the remaining port receives none. Hybrid couplers find many uses in RF circuitry. Our specific application is the elaboration of sum and difference of the signals produced by an electrostatic position pick-up in a particle accelerator.

Hybrids qualified as 'Wide-Band' commonly span two octaves of frequency, and the best ultra-wide-band devices cover about three decades. The hybrid coupler described here has a useful response from 40kHz to some 400MHz.

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1. Introduction

A hybrid coupler is a reciprocal radio-frequency building block with four ports. Signal power applied to any port is equally divided between the two adjacent ports, while the remaining port receives none. Referring to Fig. 1, it is convenient to use a matrix of scattering parameters to describe its behaviour.

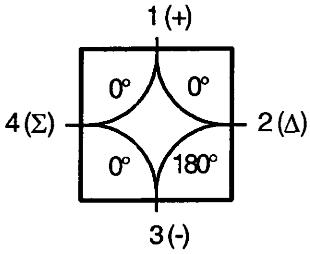

Fig. 1 Hybrid port assignments

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & -1 & 0 \\ 0 & -1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix} \quad (1)$$

This matrix is an idealised description and does not include the effects of losses, propagation delay, mismatch and impedance transformations. As can be seen, signals propagating between ports 2 and 3 are inverted. Opposing ports do not communicate, but receive half the power applied to each of their adjacent ports.

The factor $1/\sqrt{2}$ reflects the fact that the hybrid is a passive lossless network, and must conserve energy. Note that if two equal signals are applied to, e.g., ports 1 and 3, all of the input power emerges at port 4 and none at port 2. This property lends to hybrid couplers being widely used as combiners. Our specific application is the elaboration of the sum and difference of signals produced by an electrostatic position pick-up in a particle accelerator.

Hybrids qualified as 'Wide-Band' commonly span two octaves of frequency, and the best ultra-wide-band devices cover about 3 decades [1,2,3]. The hybrid coupler described here has a useful response over 4 decades, from 40kHz to some 400MHz.

2. Basic layout

The basic structure of the circuit is that of a two-port in-phase combiner and a two-port 180-degree combiner connected in parallel [4]. The diagram shown (Fig. 2) deals with the aspects of mutual coupling only, and ignores the delay inherent in the actual circuit. Note that the characteristic impedance of the Σ and Δ ports is half that of the other two ports. This is a common feature of hybrid couplers. The top transformer produces the sum of the two inputs. The lower half is a series arrangement of a Guanella type 4:1 impedance transformer [5], doubling as a balun, followed by a three-wire balun whose output is referred to ground. The third wire on this latter balun provides a path for the magnetisation current around the output load and thus improves the circuit balance for moderate to low frequencies [6]. However, without the preceding Guanella balun, it would have short-circuited the sum signal.

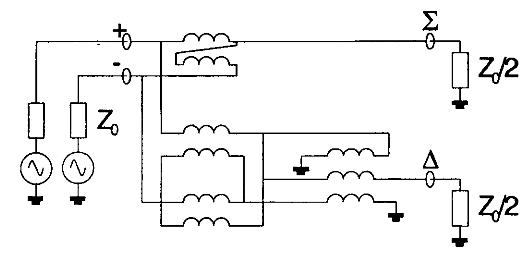

Fig. 2 Simplified schematic diagram

Ferrite beads serve to impede the flow of even mode currents on the transmission lines, allowing only odd mode signals to propagate. This mechanism breaks down when the even mode impedance becomes comparable to the source impedance, and is responsible for the value of the lower cut-off frequency, about 40kHz.

Several imperfections limit the upper cut-off frequency. First, there is the fact that the summing transformer has a null in its response at the frequency where its transmission line length equals λ/2. This occurs at about 1GHz. Furthermore, parasitic inductance in the junctions between the various elements spoils the symmetry of the circuit, causing the isolation between opposite ports to deteriorate. Finally, parasitic capacitance to the lines which carry RF voltages on their screens permits even mode currents to flow, despite the ferrite. The combined effects cause the performance of the circuit to deteriorate rapidly beyond 400MHz. In summary, the quest for bandwidth boils down to getting as much even mode inductance as possible, while keeping the leakage inductance and physical size of the elements to a minimum.

3. Mechanical construction

The coupler is made entirely of semi-rigid coaxial cables (UT47-50)[1], strung over nearly their full lengths with high-permeability ferrite beads (Philips TC7.6/3.2/4.8-3E6). Plastic sleeves keep the coax cable in the approximate centre of the ferrite beads' holes. The layout of the hybrid is quite simple and compact (Fig. 3). At the top is the summing transformer. It is constructed by cross-connecting two equal length pieces of UT47-50 folded into a U-shape. The cross-connection is introduced for symmetry reasons. Then come the two SMA input connectors. The Σ output port is mounted in between. A discrete 50Ω resistor, in parallel with the output load, provides the required 25Ω load impedance, at the cost of half the signal power.

The Guanella 4:1 balun transformer occupies the central area. Below that is the gap that contains the junction between the Guanella balun and the output balun. The Δ port connector is also mounted in this gap. Another discrete 50Ω resistor again completes the required 25Ω load for the Guanella balun, in parallel with the output balun, which has been constructed for 50Ω impedance. Again, half the signal power is sacrificed.

The output balun, also folded into a U-shape, is at the bottom. A separate 0.5 mm ∅ Cu wire forms the third winding. Since this wire primarily acts at moderate to low frequencies, its coupling with the length of UT47 coax that forms the other two windings is not critical.

The number of ferrite rings of the transformers, and therefore also the required length of coax, is chosen to centre the frequency response on the range of interest. A total of 56 ferrite rings are used.

The reason for sacrificing half of the power at each output port is that 2:1 impedance transformers would be required to perform lossless matching. Such transformers are quite complex and I have been unable to construct one with the required bandwidth and a sufficiently accurate impedance ratio, although promising schemes do exist [7]. Note, in this context, that any mismatch at the output ports is reflected as a deterioration of input port isolation and common mode rejection.

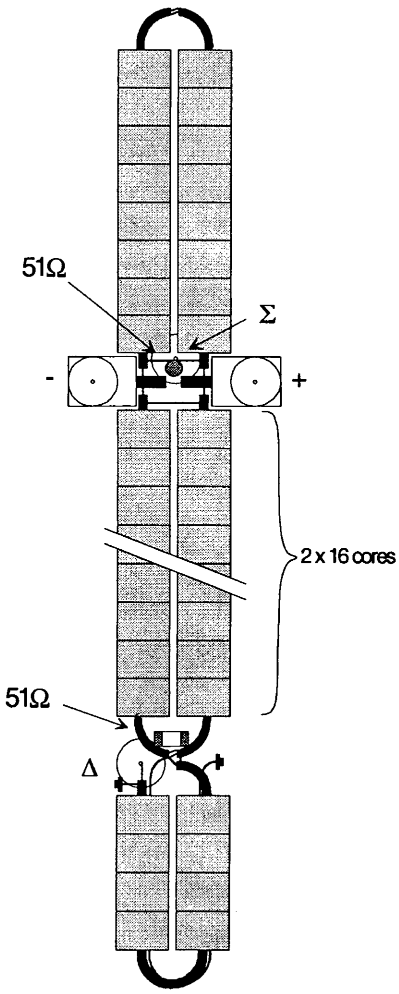

Fig. 3 Mechanical layout

Taking into account the effects of the added resistors at the Σ and Δ ports, the matrix for the hybrid becomes:

$$S = \begin{bmatrix} 0 & \frac{1}{2} & 0 & \frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} & -\frac{1}{2} & 0 \\ 0 & -\frac{1}{2} & 0 & \frac{1}{2} \\ \frac{1}{2} & 0 & \frac{1}{2} & -\frac{1}{2} \end{bmatrix} \quad (2)$$

The non-zero values of S_{22} and S_{44} reflect the fact that the corresponding ports are no longer matched. The reduced magnitudes of the other parameters reflect the losses due to the added resistors.

[1] UT47-50 is a 50Ω semi-rigid coaxial cable of $^{47}/_{1000}$" outer diameter (1.2mm).

4. Measured performance

Below are shown the 16 S-parameter plots, arranged as defined in the matrix (1). The measurement instrument, an HP8753D network analyser, has been subjected to a full two-port calibration, extending the reference plane to the ends of the connecting cables. The frequency scale goes from 10kHz to 1GHz. The vertical scales are 10dB/div for isolation and reflection, and 3dB/div for transmission parameters.

The salient features are the -3dB bandwidth of 31kHz to 690MHz, better than 20dB return loss on the + and - inputs above 1MHz, and more than 50dB of isolation between the Δ and Σ ports up to 400MHz. The transmission parameters show that the losses are 0.6dB with respect to the ideal case for mid-band frequencies.

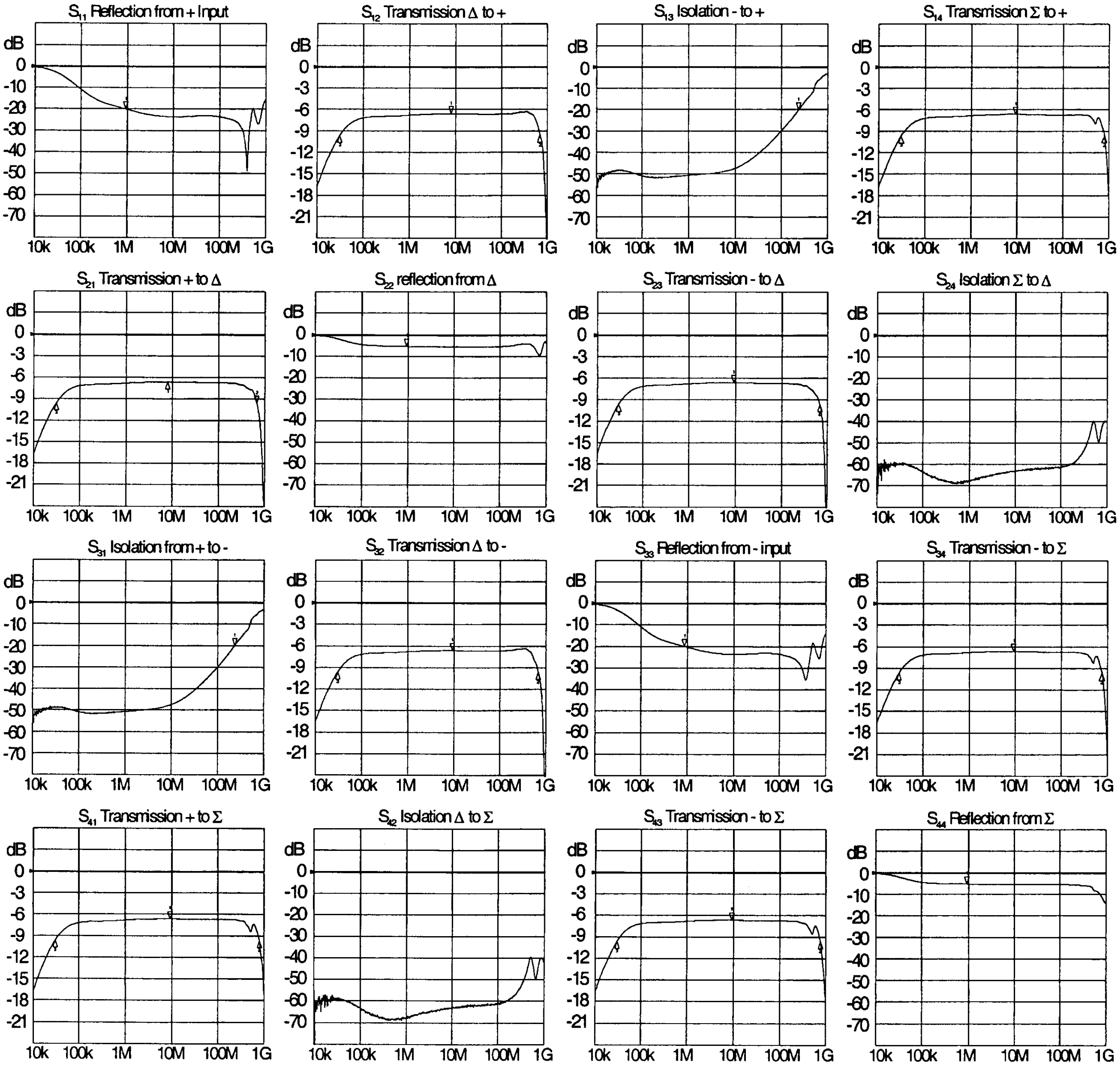

Fig. 4 S-parameters vs. Frequency

5. Special considerations

In the intended application, the elaboration of sum and difference of signals produced by an electrostatic position pick-up in a particle accelerator, the response of the Δ channel with equal inputs is of special interest. The beam will generally be close to the centre of the PU and therefore the Δ signal will be small. The position is determined by the quotient Δ/Σ and the quality of the Δ signal has a direct bearing on the measurement result.

Of interest is also the fact that, in this application, the actual source impedance -the outputs of four matched buffer amplifiers- is about 4Ω, rather than the standard 50Ω employed hitherto. This has the effect of lowering the lower cut-off frequency still further, without affecting the upper cut-off frequency, effectively extending the useful bandwidth of the device to almost 5 decades, from 4.5kHz to 400MHz. Fig. 5 bears this out.

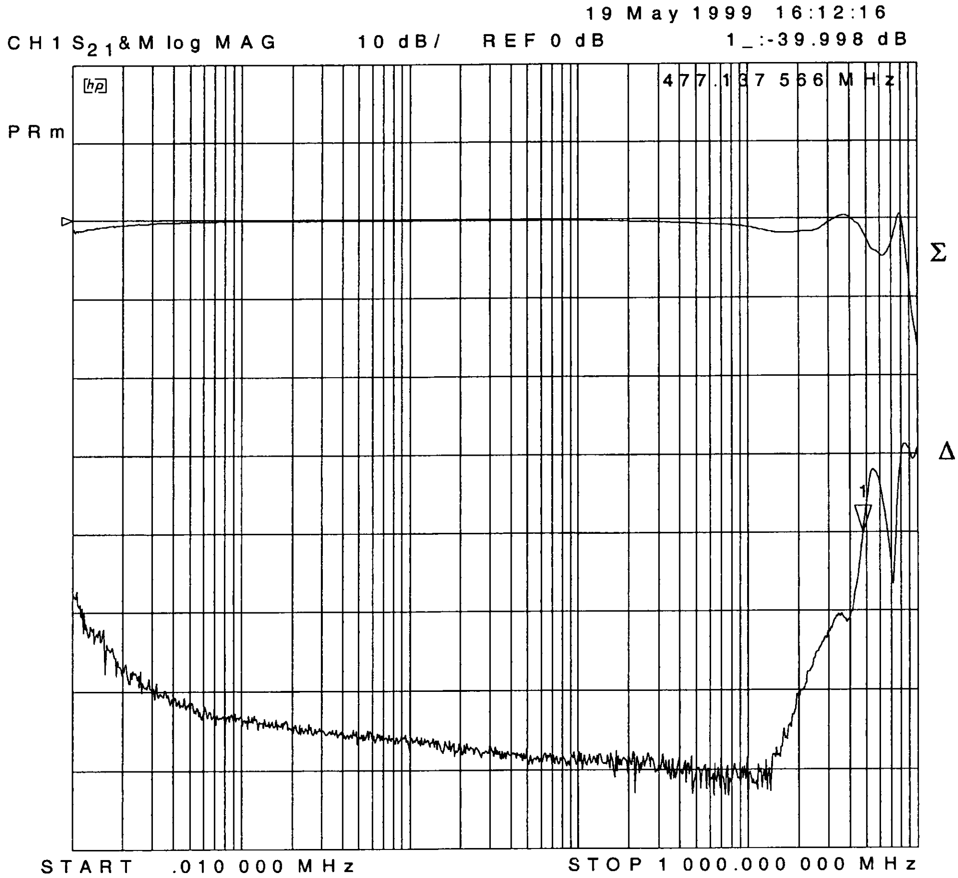

Fig. 5 Behaviour of hybrid in the intended application

6. Simulation model

In a pSpice model of the device (Fig. 6), the summing transformer and the Guanella balun were simulated by a series arrangement of an ideal transmission line element, followed by a linear transformer. The transmission line accounts for the delay, while the transformer accounts for the even mode inductance and imperfect coupling. The coupling constants of the transformers were set according to an estimate of the residual inductance of the interconnections and appeared to match actual circuit performance quite well when set to 3ppm below unity.

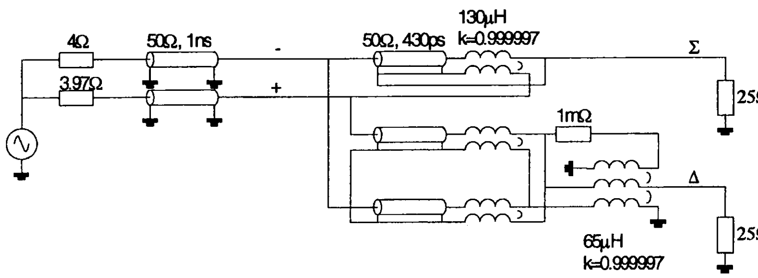

Fig. 6 Simulation model

The source resistance has been set to 4Ω. A slight asymmetry has been deliberately introduced to avoid the Δ signal to drop through the bottom. The two 1ns lines connect the hybrid to the signal source. Careful matching of the length of these lines in the actual setup is essential to maintain good common mode rejection at high frequency. In the actual circuit, I used a pair of SMA phase adjusters to absorb residual length differences. The 430ps of transmission line in the three transformers is the length required to thread through 16 ferrite cores, with a few mm to spare to make the connections. The output balun is simulated as a simple transformer. The 1mΩ resistor in the third winding is required to break a loop with zero DC resistance, which the simulator can't handle.

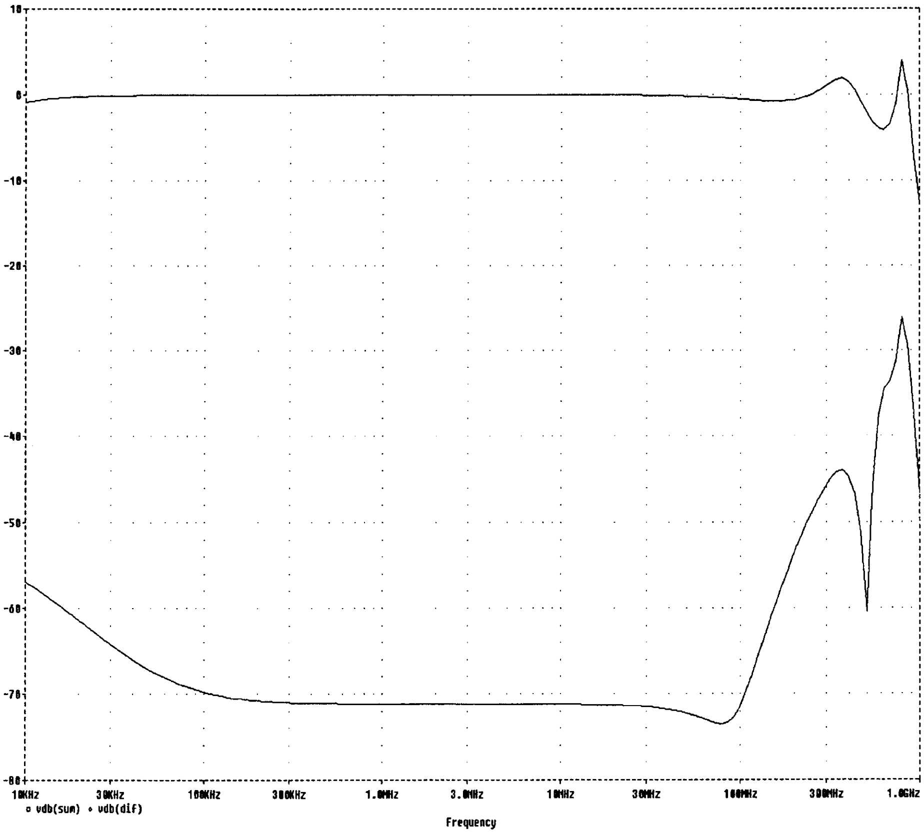

Fig. 7 Simulation results

7. Conclusions

A wide-band 180° hybrid junction has been developed, which, in the intended application of sum and difference processing of the signals from an electrostatic position pick-up in a particle accelerator, exhibits a useful bandwidth of 5 decades, from about 4kHz to 400MHz. The value of Δ/Σ for a hypothetical perfectly centred beam is better than -40dB, adequate for acquisition using a digital oscilloscope.

The pick-up measures both horizontal and vertical position in a single instrument. A further development therefore is the construction of a hybrid producing difference signals for both axes, and an overall sum.

Possibly the bandwidth of the hybrid can be extended by another octave by choosing ferrite toroids with a higher ratio of inductance factor over height A_ℓ/h, such as, e.g., the Ceramic Magnetics T250619MN100.

References:

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