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Broadband High Frequency Differential Coupler

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Abstract* - This paper describes the design methodology of a broadband, high frequent differential coupler. The output signal of this differential coupler is proportional to the difference of 2 input ports, i.e. proportional to the differential signal of the 2 inputs. This signal is made using a hybrid structure. The overall performance of this differential coupler and the hybrid structure is characterized by the differential coupling factor and by the common mode rejection ratio. A pair of broadband impedances are used to scale the 2 incoming signals with 2 complex coefficients. A symmetric structure of two identical broadband directional couplers and a symmetric power combiner are used afterwards to obtain the differential signal. The high bandwidth of both the terminations, the directional couplers and the power combiner make it possible to obtain a differential coupling factor and a common mode rejection ratio which is frequency insensitive over several decades. Measurements demonstrate a differential coupler with a bandwidth of more than 3 decades.

I. INTRODUCTION

Analog integrated circuit designs are often differential in order to be less sensitive to common mode perturbations. The operational frequencies of the differential analog designs increases towards the microwave frequencies. The measurement of high frequent differential signals therefore becomes an important topic for measuring analog high frequent devices [1], [2].

A schematic representation of the differential coupler in a measurement setup is shown in fig. 1. The directional couplers in the signal path are used to reduces the influence of the measurement setup upon the DUT. They also make it possible to perform e.g. load-pull measurements.

After these couplers, the differential signal needs to be made by making the difference of the 2 signals. Existing techniques which perform such operation can be classified in the following categories:

1. High frequent transformers make it possible to transform the differential signals into a single ended one. This solution is broadband but is limited to frequencies up to several GHz. High frequency transformers - i.e. up to 50 GHz - are not realizable.

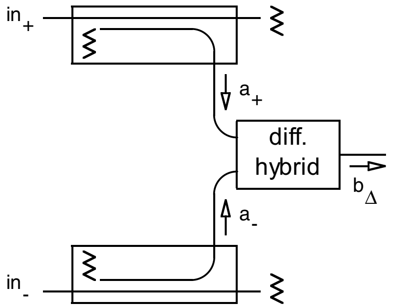

Fig. 1. Structure of the differential coupler.

2. Network analyzers which measure both incoming signals independently [2]. This might results in a loss in dynamic range if one has to subtract two almost identical signals. Hence, large common mode signals considerably reduce the dynamic range of the analyzer.
3. Several differential to single ended hybrid structures are available at microwave frequencies. These so called baluns basically splits up a singled ended signal into a differential signal. They are operational for a frequency band which is in the order of magnitude of 1 decade. They are designed to have negligible loss when converting from a single ended signal into a differential signal (or back). A Marchand balun [3], [4] - a structure of coupled lines without any resistors - or 3dB couplers like a Lange couplers [8] are often used in practice.

   The isolated ports of the couplers are most often terminated by a short circuit or an open circuit [3], [4], [5], [7]. Resistive terminations for the isolated ports are only found in some rare occasions [6]. The use of a load is avoided as mush a possible to reduce the losses in the balun.

This paper describes a new methodology to generate the differential signal with a good common mode rejection ratio (CMRR) over a broad frequency band.

The main difference with respect to the baluns are the following:

1. A differential coupler tolerates a coupling factor which differs from 3dB. This gives an additional degree of freedom since the coupling factor has an impact on the

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bandwidth of the couplers. Broadband couplers with a large coupling factor put more stringent demands on the technology used.

2. The design is fully symmetrical with respect to the 2 input signals and 2 broadband impedances. This makes it possible to rely on the broadband characteristics of the impedances to obtain a good common mode reject ratio. This is in contrast with most baluns found in the literature.
3. Terminating the isolated port of the coupler with a short or an open puts an additional constraint on the power splitter/combiner. Reference [8] uses Lange couplers with the isolated ports terminated using a short and an open. This puts the constraint on the divider: its 2 output ports must be isolated. Such a divider - a Wilkinson divider in [8] - puts a constraint on the bandwidth. The presented design makes use of couplers with matched isolated ports. This makes its possible to use a - broadband - resistive power combiner.

Section II provides a more detailed description and analysis of the proposed hybrid structure. Section IV shows measurement results of such structures build using discrete components These measurement results show that good performance can be obtain over wide frequency rang.

II. DESCRIPTION AND ANALYSIS

A. The elements of the hybrid

A schematic view of the proposed hybrid structure is shown in fig. 2. It consists out of a symmetric network - i.e. the 2 directional couplers and the power combiner - and 2 anti-symmetric impedances. Microwave bridges can be used instead of directional couplers.

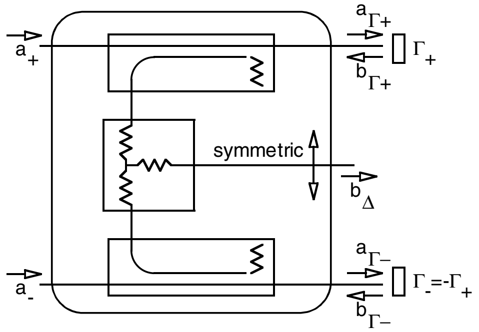

Fig. 2. Structure of the differential hybrid structure. The symmetric network consists out of 2 directional couplers and a power combiner. The anti-symmetric terminating impedances are represented by Γ_+ and Γ_-.

1. Anti-symmetric impedances

The 2 anti-symmetric impedances satisfy

$$\Gamma(f) = \Gamma_+(f) = -\Gamma_-(f) \tag{1}$$

at all considered frequencies f. It can be seen as a pair of impedances which are anti-symmetric with respect to the Smith chart. An imbalance will be denoted by Γ_Δ such that

$$\begin{aligned} \Gamma_+ &= \Gamma + \Gamma_\Delta \\ \Gamma_- &= -\Gamma + \Gamma_\Delta \end{aligned} . \tag{2}$$

Several broadband solutions can be found for the anti-symmetric impedances. Examples are

- a short in combination with an open circuit ($\Gamma = 1$).
- 2 resistive impedances satisfy $Z_- = Z_0^2/Z_+$ where Z_0 represents the characteristic impedance used.
- all pairs of impedances satisfying (1) which are both delayed with identical delay lines with a characteristic impedance Z_0 and a delay τ

$$\Gamma_-(f)e^{-j\gamma(f)\tau} = -\Gamma_+(f)e^{-j\gamma(f)\tau} \tag{3}$$

If $\gamma(f)$ is a complex valued function, then lossy delay lines are involved.

2. The directional couplers (or microwave bridges)

Both the directional couplers / microwave bridges and the power combiners are characterized using 3-by-3 matrices. The port numbering can be seen in fig. 3. The couplers of the positive and negative signal path are symbolized using S-matrices $[S^{D_+}]$ and $[S^{D_-}]$ respectively. The ideal case assumes that both couplers are identical. This motivates why the analysis is carried out using the common mode and the differential S-parameters

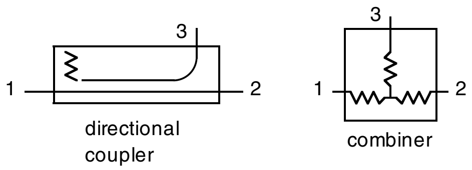

Fig. 3. Port numbering of the directional coupler and the power combiner.

$$[S^D] = \frac{1}{2}([S^{D_+}] + [S^{D_-}]) \tag{4}$$

$$[S^{D_\Delta}] = \frac{1}{2}([S^{D_+}] - [S^{D_-}]) \tag{5}$$

B. Circuit Analysis

A full blown sensitivity analysis results in very complex equations which give very little insight into the design problem of the hybrid structure. This is why the analysis is split into several separate sensitivity analyses.

1. Basic analysis

The basic operation of the hybrid structure can easily be understood when assuming ideal directional couplers and power combiners. The waves a_+ and a_- first travel through the 2 identical couplers. Then they are reflected onto the asymmetrical impedances such that $b_{\Gamma_+} = \Gamma S_{12}^{D} a_+$ and $b_{\Gamma_-} = -\Gamma S_{12}^{D} a_-$. Assuming ideal couplers with an infinite directivity implies that the output of the directive couplers equals $S_{31}^{D} \Gamma S_{12}^{D} a_+$ and $-S_{31}^{D} \Gamma S_{12}^{D} a_-$. Summing these two signals using the power combiner results in an output signal which equals

$$b_\Delta = S_{31}^{C} S_{31}^{D} \Gamma S_{12}^{D} (a_+ - a_-) \tag{6}$$

2. Finite directivity of the couplers

The finite directivity of the couplers implies that a part of the incoming energy will be transformed into a common mode signal. This implies that

$$b_\Delta = S_{31}^{C} S_{31}^{D} \Gamma_+ S_{12}^{D} (a_+ - a_-) + S_{31}^{C} S_{23}^{D} (a_+ + a_-) \tag{7}$$

Hence the common mode rejection ratio

$$\mathrm{CMRR} = \frac{\left|S_{31}^{D} \Gamma_+ S_{12}^{D}\right|}{\left|S_{23}^{D}\right|} \tag{8}$$

will heavily depend on the directivity of the coupler. Note that the CMRR is not proportional to the coupling factor of the directive coupler. The fact that $\left|S_{31}^{D}\right|$ and $\left|S_{23}^{D}\right|$ often have the same frequency behavior implies that it is possible to obtain excellent CMRR over a wider frequency band.

3. Influence of circuit imbalances

An asymmetry in the directional couplers and the power combiner reduces the CMRR. A first order perturbation analysis immediately shows that

$$\begin{aligned} b_\Delta &\cong S_{31}^{C} S_{31}^{D} \Gamma_+ S_{12}^{D} (a_+ - a_-) \\ &+ (S_{31}^{C} S_{31}^{D} \Gamma_+ S_{12}^{D_\Delta} + S_{31}^{C} S_{31}^{D_\Delta} \Gamma_+ S_{12}^{D})(a_+ + a_-) \cdot \\ &+ S_{31}^{C_\Delta} S_{31}^{D} \Gamma_+ S_{12}^{D} (a_+ + a_-) \end{aligned} \tag{9}$$

Imbalances of the asymmetric impedance, generate similar results

$$b_\Delta \cong S_{31}^{C} S_{31}^{D} S_{12}^{D} (\Gamma (a_+ - a_-) + \Gamma_\Delta (a_+ + a_-)) . \tag{10}$$

These results imply that the CMRR will be proportional to the relative imbalance of the different components.

$$\mathrm{CMRR} \cong \frac{\left|S_{31}^{D} \Gamma_+ S_{12}^{D}\right|}{\left|S_{23}^{D}\right|} + \frac{\left|S_{12}^{D}\right|}{\left|S_{12}^{D_\Delta}\right|} + \frac{\left|S_{31}^{D}\right|}{\left|S_{31}^{D_\Delta}\right|} + \frac{\left|S_{31}^{C}\right|}{\left|S_{31}^{C_\Delta}\right|} \tag{11}$$

4. Isolation of the power combiner

An ideal power combiner isolates the different inputs. A Wilkinson power combiner is a possible realization of such combiner. The main advantage of this approach is that the matching of the output of the directional coupler ($\left|S_{33}^{D}\right|$) is not critical.

A resistive power combiner can be made over a high bandwidth. It does not provide any isolation between the different ports. Hence, the output of the directional coupler must be matched in order to reduce the cross-talk from one coupler to the other. This is why a directional coupler is used whose isolated port is terminated using a resistor.

III. PRACTICAL REALIZATION

A wide range of possible hardware realizations are possible:

- The directional couplers can be made using coupled transmission lines in various configurations (strip-line, waveguide, coplanar waveguide...) [9], [10]. They can also be replaced by microwave bridges which can be seen as the high frequent equivalent of a Wheatstone bridge.
- Various types of power combiners can be used. Examples are resistive power combiner, a Wilkinson power splitter,...

The directional couplers and the power combiner can even be combined into 1 microwave device which consists out of 3 coupled lines. Fig. 4 shows a possible configuration of such setup using coupled thick rectangular bars. The left bar and the centre bar is the first coupler, while the right bar and the centre bar is the second coupler. Combining the power of the 2 waves is done at the level of the electrical fields. The setup of 3 coupled lines requires, however, that the coupling between the left and the right bar is negligible. This is a feasible requirement when working with coupled bars [10].

IV. MEASUREMENT RESULTS

Two experimental setups are made in order to demonstrate the hybrid structure. The first setup uses microwave bridges of the HP8515A test set. These bridge operate in the 10MHz-26.GHz frequency range. A second setup uses directional couplers of the HP8517B test set. These are build to operate in the 45MHz-50GHz frequency range.

A. Hybrid using microwave bridge up to 26.5GHz.

The setup was build using standard 3.5mm technology components:

- A HP11667B resistive power splitter which is used as power combiner

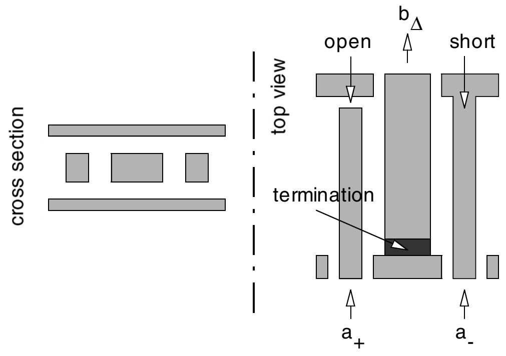

Fig. 4. Differential hybrid structure composed out of 3 coupled thick rectangular bars. The 2 directional couplers and the power combiner are joint into 1 structure. The left and the right bar are part of the 2 couplers. The centre bar is common for the 2 couplers. The latter is also used as power combiner since it combines the 2 electrical fields. No additional power combiners are necessary.

- A standard short circuit
- An open ended rigid coaxial line
- 2 broadband microwave bridges coming from an HP8515A S-parameter test set.

All measurements are performed using calibrated network analyzers. The measurements up to 300MHz are performed using a HP8753C. The measurements in the range from 300MHz up to 26.5GHz are obtained using a HP8510C.

1. The Microwave bridge

Fig. 5 and 6 show the coupling factor and the directivity of the microwave bridges used. Both the coupling factor and the insertion loss equal 6 dB over the frequency range of 10 MHz up to 26.5 GHz. The directivity is better than 30 dB in this frequency range.

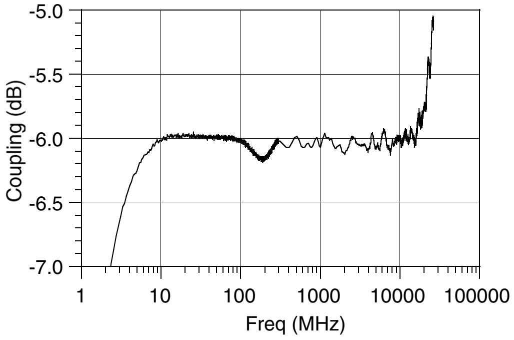

Fig. 5. Coupling factor of the microwave bridges.

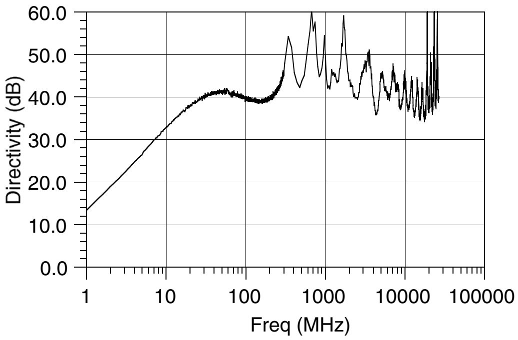

Fig. 6. Directivity of the microwave bridges.

2. The anti-symmetric impedances

An open and a short circuit are used as anti-symmetric impedances. The open circuit has been realized using an open-ended rigid coax. The length of this rigid coax is adapted such that the open circuit is at the same electronic length than the transmission line in front of the short circuit.

The reflection factors of the short and the open are not perfectly anti-symmetrical at higher frequencies. This imbalance comes from the experimental nature of the setup and can be reduced in practice.

3. The differential hybrid structure

Fig. 7 and 8 show the coupling factor of the hybrid. It can be seen that the coupling factor is about 12dB from 10 MHz up to 10 GHz. The CMRR is better than 20dB in this frequency range. Note that the CMRR is better than 30dB in the 25MHz - 3GHz range. Hence, this differential hybrid operates over a frequency range of 3 decades.

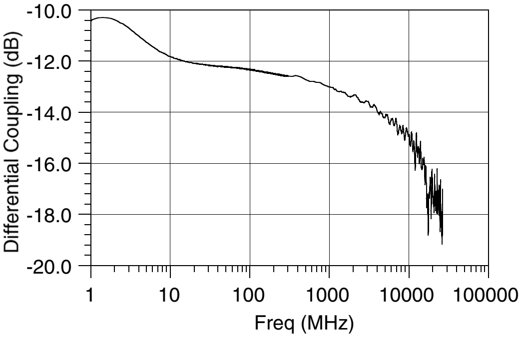

Fig. 7. Differential coupling factor of the differential hybrid structure.

Fig 9 and 10 show the relative amplitude and phase characteristic between the signal path of a_+ and a_- towards the output b_Δ. The degradation of the CMRR at higher frequencies is not introduced by the directivity of the couplers, but by the imperfections of the open and short terminations.

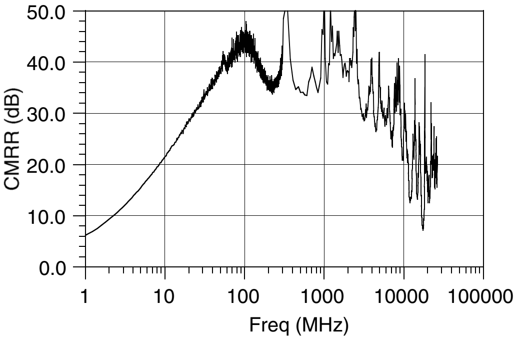

Fig. 8. CMRR of the differential hybrid structure.

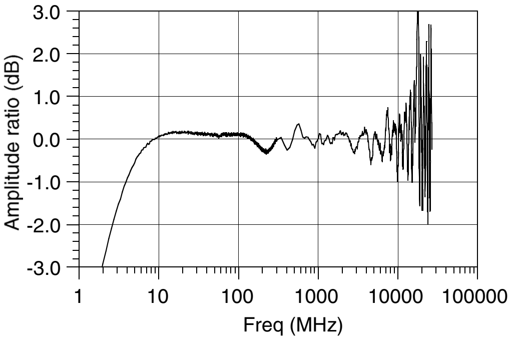

Fig. 9. Amplitude ratio between the signal path of a_+ and a_- towards the output b_Δ.

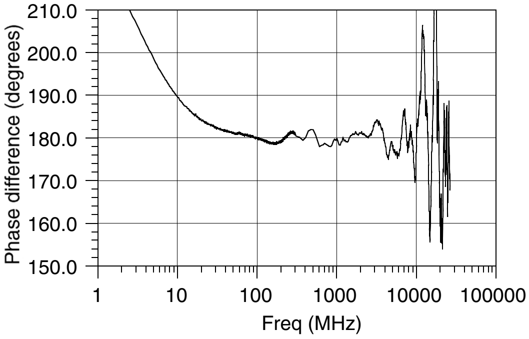

Fig. 10. Phase difference between the signal path of a_+ and a_- towards the output b_Δ.

B. Hybrid using directional coupler up to 50GHz.

The setup was build using standard 2.4mm technology components:

- A HP11667C resistive power splitter which is used as power combiner
- A standard short circuit
- A standard open circuit
- 2 broadband directional couplers coming from an HP8517B S-parameter test set.

All measurements are performed using a HP8510C calibrated network analyzers from 45 MHz up to 50 GHz

1. The directional couplers

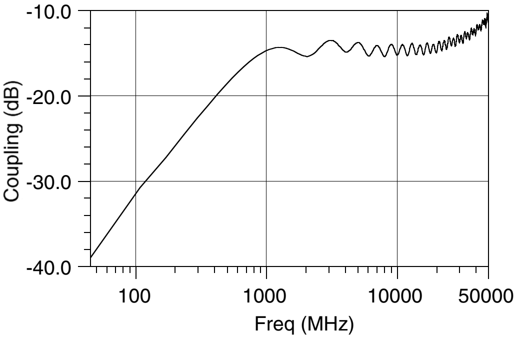

Fig. 11. Coupling factor of the 45 MHz-50 GHz directional couplers.

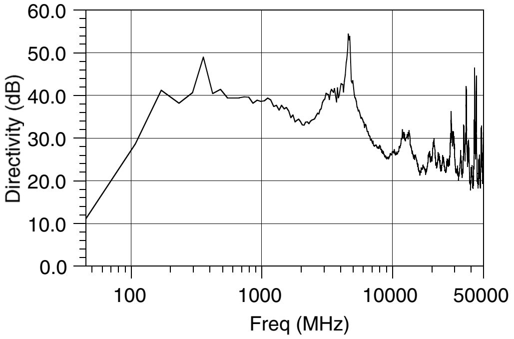

Fig. 12. Directivity of the 45MHz-50GHz directional couplers.

The coupling factor and the directivity of the 50 GHz directional couplers are shown in fig. 11 and 12. This strip-line couplers have a small coupling factor below 500 MHz. An excellent directivity (better than 25 dB) is observed between 100 MHz and 15 GHz. This directivity decreases above 10 GHz.

2. The differential hybrid.

Fig. 13 and 14 show the coupling factor of the hybrid. It can be seen that the coupling factor is about 21dB from 500 MHz up to 50 GHz. The CMRR is better than 13 dB in this frequency range. The CMRR is better than 20 dB in the 100 MHz - 17.5GHz range. This is a frequency range of more than 2 decades.

Fig 15 and 16 show the relative amplitude and phase characteristic between the signal path of a_+ and a_- towards the output b_Δ. The degradation of the CMRR at higher frequencies is introduced by the reduced directivity of the couplers.

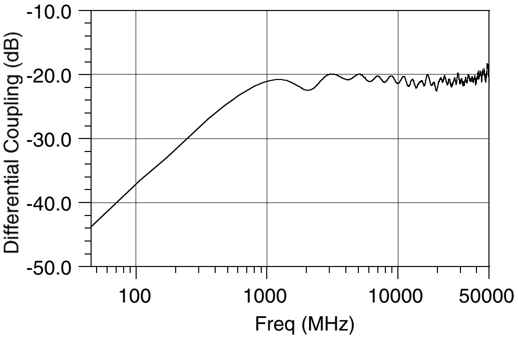

Fig. 13. Differential coupling factor of the 50GHz differential hybrid structure.

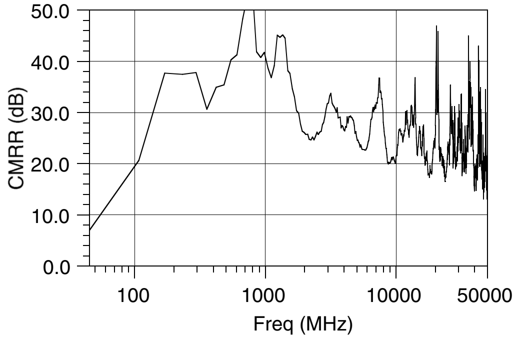

Fig. 14. CMRR of the 50GHz differential hybrid structure.

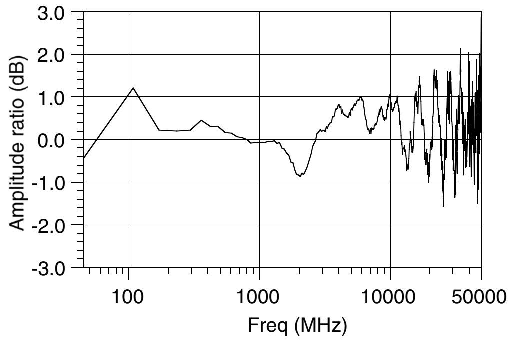

Fig. 15. Amplitude ratio for the 50GHz hybrid between the signal path of a_+ and a_- towards the output b_Δ.

V. CONCLUSIONS

This paper proposes a broadband differential coupler based on a hybrid microwave structure. The latter build using broadband microwave circuits and relies on symmetry properties. These 2 aspects make it possible to obtain good performances over several decades of the frequency.

A sensitivity analysis showed that following properties are of crucial importance for the performance:

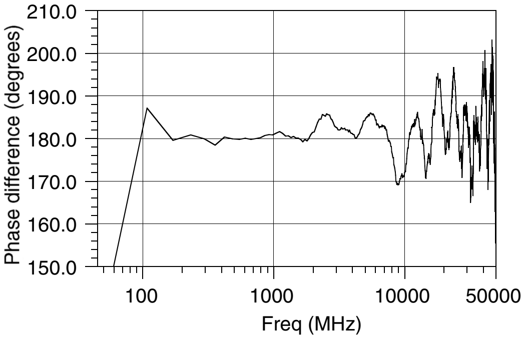

Fig. 16. Phase difference for the 50GHz hybrid between the signal path of a_+ and a_- towards the output b_Δ.

- the directivity of the directional couplers must be high. This puts a constraint on the technology used for the realization.
- the symmetry of the hybrid structure.
- the ability to make broadband impedance which are anti-symmetric on the Smith chart.

Measurements on setups constructed using discrete components show that a frequency range of 3 decades is feasible and that signals up to 50GHz can be handled.

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