S-Band Reflection Type Variable Attenuator

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***Abstract*—A reflection type variable attenuator is described in this letter. The main component of the circuit is a microstrip 3 dB quadrature coupler. The coupler is used in conjunction with two varactor diodes to vary the attenuation from 2.2 dB to 17 dB over a 40% bandwidth (2.8–4.2 GHz). If married with a programmable voltage controller, the proposed design will provide a low-cost solution for applications with narrow instantaneous bandwidth.**

***Index Terms*—Attenuator, quadrature hybrid coupler, reflection type, varactor diode.**

I. Introduction

VARIABLE attenuators may be used to control the power level of a RF source or as gain control at a receiver input. An obvious figure of merit for a variable attenuator is the attenuation range. However, depending on the application, performance issues such as bandwidth, phase variance, return loss, power handling, signal shape ("flatness"), and circuit size/cost must be considered. Papers addressing wideband and/or phase invariant variable attenuators are found in [1]–[3], exhibiting bandwidths $>$20 GHz, and phase errors $<\pm 5^\circ$. A nonreflecting variable attenuator is presented in [4] that exhibits $>$16 dB of return loss and a high power design is discussed in [5], where the maximum input power is estimated to be between 10–20 W.

This paper discusses a variable attenuator designed to operate over a 40% BW for frequencies from 2.8 to 4.2 GHz. The completed circuit is a low-cost structure comprised of a microstrip hybrid coupler combined with integrated voltage controlled capacitors (varactor diodes).

The motivation for this work is to develop an attenuator prototype that is scalable for swept-frequency signal source operation in the W-band over a 40% BW (75–110 GHz). At these frequencies, a CPW-based coupler fitted with MEMS-type variable capacitors is projected to replace the low-frequency design presented herein. This design provides an alternative to absorptive-type attenuators, where the implementation of transistors or p-i-n diodes would be costly for low-volume applications.

II. Attenuator Design

As evident from [1]–[5], many RF variable attenuator circuits incorporate four-port directional couplers with voltage controllable resistances (p-i-n diodes or MESFETs). This approach enables the signal level to be varied with bias voltage. An excellent paper analyzing a variable attenuator using a 3 dB quadrature coupler with variable resistance terminations is found in [6]. The design presented herein is supported by the attenuator analysis presented in [6] and the coupler theory discussed in [7].

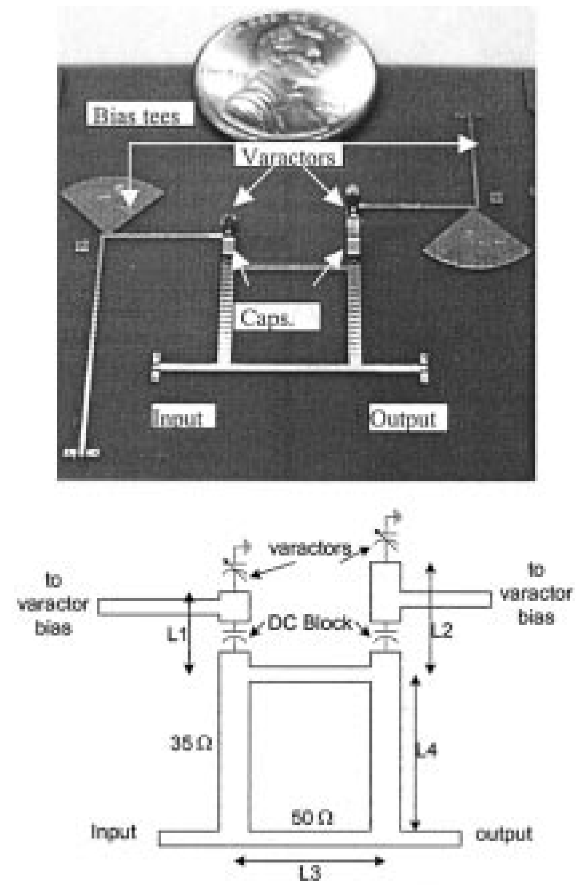

Fig. 1. Perspective photo of variable attenuator with layout; $L1 = 146$, $L2 = 286$, $L3 = 414$, and $L4 = 400$ (all in mils).

The variable attenuator circuit is shown in Fig. 1. The design consists of a four-port, 3 dB quadrature coupler comprised of microstrip lines fabricated on a 14-mil FR4 substrate. M/A COM tuning varactors (P/N: MA4ST551) with adjustable capacitance from (0.4–2) pF are located at two ports of the coupler. Bias tees comprised of high impedance lines and radial stubs are used to connect each varactor to dc, while 68 pF 0805 lumped capacitors are used as dc blocks.

Attenuation occurs as a result of destructive interference from input signal components that are reflected off of each varactor. More specifically, a signal present at the input is evenly split between the ports connected to the varactors, with a 90°-phase difference between each. Since the varactors present a purely reactive load, the signal present at each is fully reflected back into the coupler (assuming lossless varactors). The amount of power present at the attenuator output and amount of power reflected

Manuscript received November 29, 2001; revised April 22, 2002. This work was supported in part by the Anritsu Corporation. The review of this letter was arranged by Associate Editor Dr. Shigeo Kawasaki.

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Publisher Item Identifier 10.1109/LMWC.2002.801131.

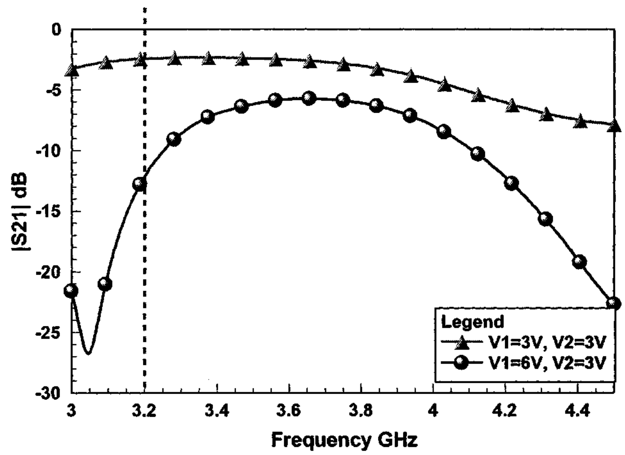

Fig. 2. Measured $|S21|$ curves for 2.5 dB and 12 dB of attenuation at a 3.2 GHz test frequency.

back to the input depends on the phase difference between the signals that are reflected from each varactor.

Equation (1) can be derived as the transmission response of the attenuator

$$S_{21}(\omega, C1, C2, \beta \cdot L1, \beta \cdot L2) = \frac{j}{2} \cdot \left\{ \exp\left(j \cdot \left(\tan^{-1}\left(\frac{-2 \cdot Zo \cdot \omega \cdot C1}{1 - (Zo \cdot \omega \cdot C1)^2} \right) - 2 \cdot \beta \cdot L1 \right) \right) + \exp\left(j \cdot \left(\tan^{-1}\left(\frac{-2 \cdot Zo \cdot \omega \cdot C2}{1 - (Zo \cdot \omega \cdot C2)^2} \right) - 2 \cdot \beta \cdot L2 \right) \right) \right\}. \quad (1)$$

From (1), S_{21} appears to be dependent on five separate variables. However, ω and β are determined by the operating frequency and $L1$ and $L2$ are chosen lengths of line inserted between each varactor and corresponding coupler port. These lengths act as phase offsets and are chosen such that the combination of varactor capacitances, $C1$ and $C2$, will provide the widest range of phase-shift and the broadest range of attenuation $|S_{21}|$. The best choice for $L1$ and $L2$ was found by solving (1) over a chosen range of potential offset lengths and then extracting the $L1$, $L2$ pair that produced the most dynamic variation in $|S_{21}|$. Thus, after further inspection of (1), S_{21} becomes a function that is governed entirely by two independent variables, $C1$ and $C2$.

III. Measurements and Results

Representative frequency response curves for two subjective bias voltage combinations are shown in Fig. 2. For a given bias combination, the attenuation response is not flat across the band. However, flat attenuation responses from 2.2 dB to 17 dB are achieved by varying the bias voltage of each varactor with frequency. Since this design is reflective in nature, undesirable return loss levels will occur; typical return loss values of >2 dB and >9 dB occur respectively at the upper (17 dB) and lower (2.2 dB) attenuation settings.

The lower attenuation level (2.2 dB) is confined by varactor loss, whereas the upper attenuation level (17 dB) is limited by frequency sensitivity. Attenuation data compiled by manually adjusting the varactor bias voltage with frequency is illustrated in Fig. 3. Voltage versus attenuation plots at tested frequencies from 2.8 GHz to 4.2 GHz with a 100 MHz step were compiled; a representative plot at 3.2 GHz is given in Fig. 4. Plots such as these will provide the necessary data needed to operate the attenuator effectively.

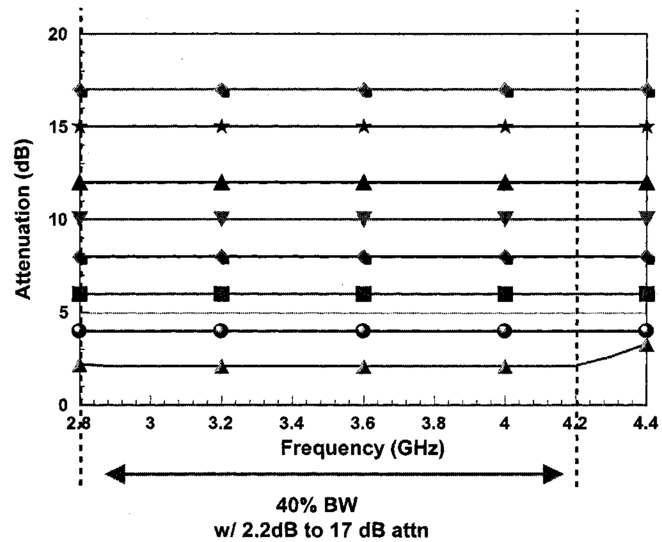

Fig. 3. Measured attenuation levels over a 40% BW.

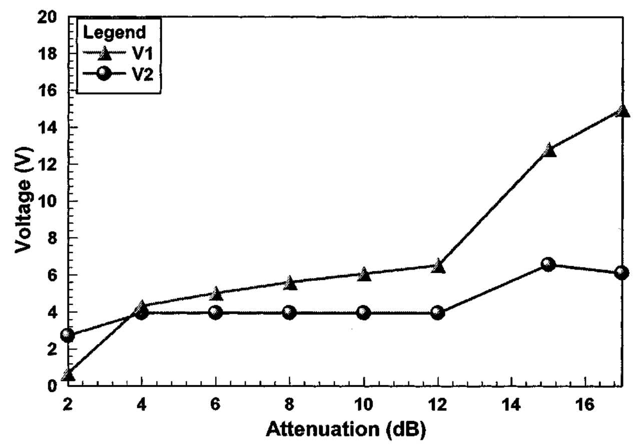

Fig. 4. Representative plot of voltage versus attenuation at 3.2 GHz.

The sensitivity in attenuation was examined in two ways. First, the variation over small frequency bands was measured with fixed bias voltages. At attunuation levels >12 dB, the variation was ±2 dB over ±0.05 GHz at a test frequency of 3.2 GHz. The variation reduces to ±0.5 dB over spans of ±0.01 GHz and decreases monotonically with attenuation level. Second, the sensitivity of attenuation versus bias voltage was investigated. A typical change was ±0.25 dB for a ±0.05 V change in the bias at 3.4 GHz. Thus, the presented design is best suited for applications with narrow instantaneous bandwidth, such as with the aforementioned swept-frequency signal source.

IV. Conclusion

This paper examines the design and operation of a variable attenuator at frequencies in the S-band. It effectively attenuates

RF signals by 2.2 dB to 17 dB over a 40% BW and flat attenuation is achieved by changing the varactor bias voltage with frequency. For application with a swept-frequency signal source, a programmable voltage controller is recommended to efficiently regulate the varactor bias conditions needed to achieve a flat response at each swept-frequency point. Additionally, an isolator should be placed between the attenuator and the signal source to suppress any signal reflections.

For application in the W-band, modifications to the current design will be made that will improve the attenuation performance. Thin film MIM capacitors will be used as dc blocks, ridding the circuit of the parasitics associated with the chip capacitors, and MEMS-type capacitor banks will replace the lossy varactor diodes, enabling the minimum attenuation level to undercut the present limit of 2.2 dB.

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