RF Components and Systems

Microwave Plumbing for Systems Applications

A Passion for Plumbing

CMOS AGC Design Strategies

By TORE N. ANDERSON
AIRTRON INC.
LINDEN, NEW JERSEY

and harmonic reduction for microwave systems. A number of the techniques which are being developed to reduce spurious radiation and the response of receivers to extraneous signals are discussed.

Tracking Antennas have become more widespread in the use of higher frequency systems. The concept of being able to control these shortcomings by a closed loop servo system that can be included as part of advanced application components.

Byer switch technology has been developed for several applications. Coolidge-pressed crystal detectors of these applications are used as switch functions in a number of devices.
FEATURES

COVER FEATURE: THEN AND NOW

22 The Look Forward in Microwave Plumbing for Systems Applications
Tore N. Anderson, Airtrom Inc.
First published in July/August of 1958, this article discussed the application of new microwave ferrite components to missile guidance radars, tracking antennas and microwave relays

32 A Passion for Plumbing: 50 Years of Waveguide Assemblies and Components
Nigel Bowes, Credlowan Limited
A personal look back at Tore Anderson's original 1958 article, along with an analysis of the past, present and future of waveguide assemblies and components

TECHNICAL FEATURES

66 An Enabling New 3D Architecture for Microwave Components and Systems
Zoya Popovic, Sebastien Roudineau and Dejan Filipovic, University of Colorado; David Sherrer, Chris Nichols, Jean-Marc Rollin and Ken VanHille, Rohm and Haas Electronic Materials
Introduction to a manufacturing technology designed to produce 3D metallic-dielectric components to go directly from 3D CAD drawings to 3D miniature circuit components

88 Design of a Microwave Group Delay Time Adjuster and Its Application to a Feedforward Power Amplifier
Heungjaa Choi and Yongchae Jeong, Chonbuk National University; J.S. Kenney, Georgia Institute of Technology; Chul Dong Kim, Sewon Tetelet Inc.
Design, fabrication and measurement of a microwave group delay time adjuster and base station feedforward power amplifier

104 High Efficiency Broadband Power Amplifiers
Use of load pull design techniques and synthesis of broadband load networks in the design of broadband high efficiency power amplifiers
As linear modulation and demodulation is adopted in communication systems for spectrum efficiency, the system performance is limited due to nonlinearity, particularly in the power amplifier. The nonlinearity of a system can be explained as AM-AM, AM-FM, intermodulation distortion (IMD) and adjacent channel leakage ratio (ACLR). Several linearizing techniques have been introduced to overcome these nonlinearities.  

When a digital/analog predistortion or a FFW technique is applied to the nonlinear system, a group delay time matching as well as amplitude and out-of-phase matching are critical. While a variable attenuator and a phase shifter are widely used for the magnitude and phase control, there are few circuits available for control of the group delay time.

Moreover, a feedback receiving signal originating from the transmitter (Tx) antenna of the same site, deteriorates the performance of

Heungjae Choi and Yongchae Jeong
Chonbuk National University
Jeonju, Korea

J.S. Kenney
Georgia Institute of Technology
Atlanta, GA

Chul Dong Kim
Sevon Teletech Inc.
Kyungki, Korea
the received (Rx) signal and results in co-channel interference in the repeater system. The delay time of the co-channel interferer from Tx to Rx is different, case by case, and due to environmental conditions. The amplitude, phase and electrical delay time of the correction signal should be adjusted to effectively cancel the broadband interferer.\(^5\)^\(^6\)

Until now, there have been few microwave circuit GDTAs. A GDTA, consisting of different paths having different physical length, was introduced.\(^7\) However, it could not control the group delay continuously. In this article, a microwave GDTA is proposed that is capable of continuous group delay time control. The proposed GDTA is expected to play a key role in a number of applications where group delay time compensation is critical for broadband signal cancellation. To show its validity, a GDTA and base station FFW PA system were designed, fabricated and measured, using the proposed GDTA as an application example.

**ADJUSTABLE GROUP DELAY THEORY**

A group delay gives the measure of how long it takes a signal to propagate through a system. In general, the rate of change of the total phase shift with respect to angular frequency is called the group delay (GD), and is defined as \(^8\)

\[
GD = \frac{\phi}{\omega} 
\]

(1)

where

\[\phi = \text{total phase shift}\]

\[\omega = \text{angular frequency}\]

Also, the group delay flatness in the operating frequency band is an important parameter for observing the phase linearity of a receiver system, transmitted signal and so on.

To find the method to control the group delay, it is necessary to analyze a shunt resonance circuit, as shown in **Figure 1**. The input admittance of the resonance circuit is expressed as

\[Y_{in} = Y_0 + j \left(\omega C - \frac{1}{\omega L}\right)\]

(2)

and the transmission characteristic can be expressed as

\[
S_{21} = \frac{2Y_0}{\sqrt{4Y_0^2 + (\omega C - 1/\omega L)^2}} \exp\left[j \tan^{-1}\frac{1 - \omega^2 LC}{2\omega L C_0}\right]
\]

(3)

If the particular resonance frequency, \(\omega C = 1\) of the parallel resonator is maintained, the magnitude and the phase coefficient would be kept constant. Then GD, the differential phase component of the transmission coefficient with respect to the angular frequency, can be derived from Equation 4 at the particular resonance frequency, by using Equations 1 and 3.

\[
GD = \frac{2Y_0 L \left(1 + \omega^2 LC\right)}{4\omega^2 LC Y_0^2 + \left(1 - \omega^2 LC\right)}
\]

(4)

From Equation 4, the group delay time increases proportionally to the capacitance. On the contrary, as the inductance increases, the group delay time decreases, proving the inverse proportionality to the inductance. Keeping the resonant frequency fixed, the group delay time can be adjusted by several combinations of a capacitance and an inductance.

**IMPLEMENTATION AND MEASUREMENT OF THE GDTA**

**Varactor Diode Measurement**

A varactor diode is a semiconductor device that is widely used in many applications where a variable capacitance is required. The operation of the varactor diode is based on the fact that a reverse biased PN junction acts as a variable capacitor. The diode capacitance versus reverse voltage of the Sony 1T362 device used has a variation of approximately 2.3 to 100 pF, as shown in **Figure 2**.

**Variable Equivalent Inductor and the GDTA Unit**

There are few variable inductors in microwave devices. Even though there is an active inductor using a gyrator structure that can change the inductance, the quality factor (Q) is not high enough and changes according to the control voltage.\(^9\)^\(^10\) For that reason, the active inductor is not yet widely used. The series combination of a lumped inductor and varactor diode can be used as a variable equivalent inductor. Since it is difficult to fabricate high Q inductors with a small tolerance, however, the combination of varactor diode and lumped inductor is not suitable. A transmission line of characteristic impedance \(Z_0\) terminated with a varactor, can also be used as a variable inductor, as shown in **Figure 3**. A transmission line characteristic shifts from capacitive to inductive, as shown in **Figure 4**. However, the
The physical length of a transmission line is too long in case of a low operating frequency.

In this work, a high impedance transmission line, terminated with a varactor, is used to implement the variable inductor. Figure 5 shows the lumped element equivalent circuit of the transmission line, where $Z_4$ and $\theta$ are the characteristic impedance and electrical length of the transmission line, respectively. The values of the equivalent lumped elements are

$$I_4 = \frac{Z_4 \sin \theta}{\omega}, \quad C_3 = \frac{1 - \cos \theta}{Z_4 \sin \theta}$$

Using the varactor diode and the proposed variable equivalent inductor, the GDTA unit shown in Figure 6 was designed. The varactor diode is operated as the variable capacitor, and the high impedance transmission line terminated with the varactor diode is operated as the variable equivalent inductor.

The transformation procedure of the variable equivalent inductor is depicted in Figure 7. The capacitor $C_3$ denotes the variable capacitance and $C_2$ is used for the variable equivalent inductor with the high impedance transmission line, respectively. The high impedance transmission line was replaced with the lumped element equivalent circuit. Since $C_3$ shares node A with $C_1$, and $C_1$ shares node B with $C_4$, these pairs of capacitors can be substituted with $C''$ and $C_3 + C_4$. Finally, $C_3 + C_4$ can be represented as $C''$ and the series connection of $L_1$ and $C'$ can be substituted with $L'$. Equation 6 shows the equivalent reactance of the transmission line terminated with the varactor diode. As long as the equivalent reactance ($X_L$) is positive, it has an inductive characteristic. Therefore, as $C'$ is varied, a variable inductance can be obtained.

$$X_L = \frac{\omega^2 L C'}{\omega^2 C' + 1}$$
TABLE II
MEASURED RESULTS FOR THE BALANCED GDTA

<table>
<thead>
<tr>
<th>Group Delay (ns)</th>
<th>$S_{21}$ (dB)</th>
<th>$S_{11}$ Max (dB)</th>
<th>Control Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>908.5 MHz</td>
<td>911 MHz</td>
<td>914 MHz</td>
<td></td>
</tr>
<tr>
<td>1.005</td>
<td>1.041</td>
<td>1.025</td>
<td>-0.65</td>
</tr>
<tr>
<td>2.000</td>
<td>2.010</td>
<td>1.970</td>
<td>-1.36</td>
</tr>
<tr>
<td>3.051</td>
<td>3.077</td>
<td>2.986</td>
<td>-1.96</td>
</tr>
<tr>
<td>4.021</td>
<td>3.938</td>
<td>3.792</td>
<td>-2.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-2.71</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-2.71</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-2.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>19.8</td>
</tr>
</tbody>
</table>

The values of the variable capacitor and inductor are controlled by two separate bias voltages that must satisfy the fixed resonance condition. The measured results of the proposed GDTA unit, tested at 911 MHz, are shown in Table I. As GD is increased, the reflection characteristics are getting increasingly worse, due to the parasitic component of the varactor diode.

The Balanced GDTA

In order to obtain better reflection characteristics of the GDTA, a balanced GDTA structure is proposed and shown in Figure 8. It is composed of two hybrid couplers (RF Power, S03A885N1) and two unit GDTAs. The overall circuit size is 79 × 39 mm, as shown in Figure 9. The implemented GDTA was tested in the Korean RFID frequency band (908.5 to 914.0 MHz). The group delay measurements of the proposed balanced GDTA are shown in Table 2 and Figure 10.

Although a group delay time variance greater than 3 ns could be obtained, the transmission and the group delay time flatness in the high group delay time region are in a trade-off relationship, so that there was no choice but to limit the actual variation range to 3 ns. In that case, the magnitude flatness is less than 0.1 dB in the pass band and the maximum reflection coefficient is approximately –24.4 dB. These satisfactory results can be applied to systems where the group delay time matching with good flatness is critical.

BASE STATION FFW PA DESIGN USING THE PROPOSED GDTA

To obtain broadband signal cancellation, broadband amplitude, out-of-phase and group delay matching are
One of the several advantages of the GDTA is that the group delay time matching is much easier to achieve by just adjusting the control voltages.

**Figure 12** shows the group delay time matching process of the carrier cancellation loop and IMD cancellation loop. After finishing the coarse tuning using a coaxial cable, the fine-tuning is done very easily with simple voltage controls. The blue lines are the amount of the time delay of the main and error amplifier path, and the green and red lines represent the time delay before and after the fine-tuning, respectively. The mismatch of the carrier cancellation loop is due to the poor group delay flatness of the main amplifier.

**Figure 13** shows the signal cancellation loop suppression results, using the proposed GDTA, measured with a network analyzer. The proposed canceller cancels the input signal by more than 25 dB from 869 to 894 MHz. The IMD cancellation characteristic using the proposed GDTA is also shown. The input signal is cancelled by more than 30 dB within 850 ± 50 MHz. The frequency bandwidth, in which the signal is cancelled more than 20 dB, is greater than 100 MHz.

For experimental verification, the output power spectral density of the FFW PA was measured with and without the FFW loop, using a forward-link CDMA 1S-95A four-carrier signal for the digital cellular band. These measurement results are shown in **Figure 14**. The ACLRs at 3.125 and 4.375 MHz offset are shown through the output dynamic range, and the measured power spectral density of the implemented FFW PA.
at an average output power of 40 dBm is shown before and after cancellation. The ACLR at a 3.125 MHz offset is -52.12 dBc, improved by approximately 17.2 dB by the cancellation. The amount of improvement is smaller than expected from the results shown on the network analyzer because of the limitation of the measurement setup. The proposed system shows excellent linearity throughout the output dynamic range.

CONCLUSION

A new GDTA unit was designed that can control the group delay time of a signal using a parallel resonant circuit. Keeping the resonance frequency fixed, the group delay time can be adjusted by the combination of values of capacitance and inductance through a simple voltage control. The fabricated balanced GDTA improves the poor reflection characteristics of the single GDTA unit and offers a group delay time variation of approximately 3 ns. Also, the validity of the proposed GDTA was established by applying the circuit to a feedforward linearization. The pro-

![Fig. 13 Carrier cancellation loop suppression of the FFW PA using the GDTA (a) and IMD cancellation loop (b).](image)

![Fig. 14 Measured ACLR characteristic over the dynamic range (a) and power spectral density of the FFW PA using GDTA (b), with and without the FFW loop.](image)

GOT QUESTIONS? NEED QUICK ANSWERS?

Visit our website or contact our applications engineers for fast solutions to your component question.

www.e-meca.com

Application Notes - Data Sheets - Product Sweeps

- Directional Couplers
- Hybrid Couplers
- Power Divider/Combiners
- Fixed Attenuators
- Isolators/Circulators
- RF Loads
- DC Blocks
- Bias Tees

BTS/IBW Couplers

WiMAX/WIFI

Isolators/Circulators

7/16 DIN Loads

Bias Tees

DC Blocks

Rugged and Reliable RF/Microwave Components Since 1961 - Made in USA

MECA Electronics, Inc.

866-444-6322 | sales@e-meca.com | www.e-meca.com

459 East Main Street, Denville, NJ 07834 T. 973-625-0661 F. 973-625-9277

Visit http://mwj.hotims.com/16338-83
posed GDTA will contribute not only to the improvement of the quality of a communication, but also to the simplification of the group delay time tuning procedure of a communication system.

ACKNOWLEDGMENT

This article was partially supported by the CBNU fund for overseas research, 2006 (OR-2006-4).

**References**


Heungjoon Choi received his BS and MS degrees in electronic engineering from Chonbuk National University, Jeonju, Korea, in 2004 and 2006, respectively. He is currently working toward his PhD degree. His research interests include broadband linearization and high-efficiency RF PAs.

Yongchae Jeong received his BS, MS and PhD degrees in electronic engineering from Sogang University, Seoul, Korea, in 1999, 1991 and 1996, respectively. From 1991 to 1996, he was a senior engineer in the information and communication division of Samsung Electronics. Since 1996, he has been in the division of electronics and information engineering at the Integrated Circuit Design Education Center of Chonbuk National University, Jeonju, Korea. He is currently an associate professor teaching and conducting research in the areas of microwave devices, base station amplifiers, linearization technology and RFIC design.

J. Stevenson Kenney received his BSEE, MSEEE and PhD degrees in electronic engineering from the Georgia Institute of Technology in 1983, 1990 and 1994, respectively. He has over 14 years of industrial experience in wireless communications. He has held engineering and management positions at Electronic Sciences, Scientific Atlanta, PacTel Monolithics and Spectran. In January 2000, he returned to Georgia Tech as an associate professor in electrical and computer engineering. His research interests include acoustics, microsystems and microwaves.

Chul Dong Kim received his BS degree in electronic engineering from Seoul National University, Seoul, Korea, in 1997, and his PhD degree from the University of Wisconsin, Madison, in 1999. He is currently president and chief executive officer (CEO) of Seoul Telecom Inc., Kuilsan, Korea, a company specializing in RF PAs.