SPDT switch MMIC enables high-performance Ka-band Tx/Rx module

Commercially available components are often insufficient for the most demanding high-frequency applications. In these instances, customizing an advanced MMIC solution can enable higher-level system performance beyond what is possible using standard microwave or millimeter-wave devices.

By Edward Brown, David Snodgrass and Mark Hebeisen

System integrators have long recognized that high-frequency subsystem design is not a "one size fits all" arena. Increasing demands on spurious suppression, switching speed, power handling, and reduced form-factors have put pressure on module suppliers to push the envelope of their legacy designs. Having a variety of diverse semiconductor options at one's disposal is proving to be a key enabler to efficiently configuring optimal subsystem solutions. One example of how semiconductor design experience can be leveraged as part of the design of higher-level systems is the development of a Ka-band PIN diode SPDT switch MMIC by Endwave's internal semiconductor team. This custom chip design was undertaken to support the development effort for a cost-effective, high-power, extremely compact, Ka-band multichannel radar transceiver module.

The upfront portion of the design process focused on the evaluation and, ultimately, the exclusion, of other available switch technology and topology options. Subsequently, when no commercially available solution in that technology flavor was available, a high-power, fast-switching Tx/Rx MMIC switch was custom-designed and characterized. This chip provides well over 4 W of power-handling capability, exhibits nanosecond switching speed, and paves the way for a condensed module footprint, making it ideal for emerging Ka-band transceiver applications.

Millimeter-wave technologies are increasingly called upon for advanced defense electronics, homeland security and telecommunications applications. This is due in large part to their unique ability to carry large amounts of data, to provide higher resolution for radar systems, to penetrate certain structures and to provide solutions that are small, lightweight, and high performance. Millimeter-wave time division duplex (TDD) transceiver systems require a means to alternately connect the antenna to the transmitter output and the receiver input. Examples of such systems include radar, half-duplex data links, Internet-protocol-based (IP-based) wireless LAN's, and millimeter-wave imagers. The preferred method of establishing these connections in space-constrained and cost-sensitive applications is usually through the use of a Tx/Rx switch, as shown in Figure 1.

An ideal Tx/Rx switch is characterized by:

■ Low insertion loss in the selected transmission path to minimize receiver noise figure and maximize transmitter power delivered to the antenna.

■ High off-state isolation in the deselected transmission path to reduce interactions and the potential of the high-power transmitter damaging sensitive receiver circuitry.

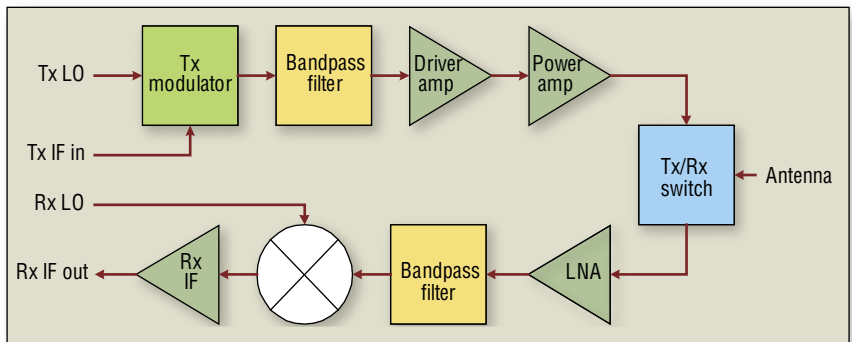■ High-power handling capability to support longer-range operation.

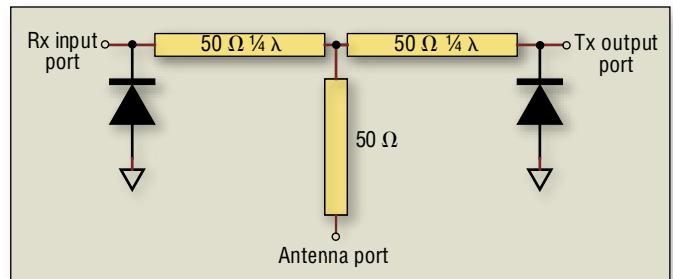**Figure 1. Generic TDD transceiver block diagram.**

Figure 2. SPDT Tx/Rx switch (bias circuitry not shown).

■ Fast transitions between switching states to reduce radar blind times and increase throughput in communication applications.

■ Low cost to reduce implementation expenses.

■ Small physical size to support tight-fitting and portable applications.

■ Simple drive/control circuit requirements to reduce complexity and power consumption.

The design example presented is a 4 W GaAs MMIC PIN diode SPDT switch designed to exhibit these desirable characteristics over a narrow bandwidth within the Ka band (27 GHz to 40 GHz). However, the switch implementation is quite flexible and it can be readily adapted to other TDD applications and operating frequencies. The design approach, options, and constraints are described, as are MMIC fabrication process parameters, simulation predictions, and measured performance results. Endwave believes that the performance of the device described exceeds that of any commercially available MMIC switch operating at Ka band.

Switch performance goals

The switch performance goals were derived from the radar transceiver requirements and its proposed implementation. Table 1

Parameter	Limit
Frequency range	Ka band, 6% bandwidth
On-state insertion loss	≤0.7 dB
Off-state isolation	≥25 dB
0.1 dB compression	≥4 W (+36 dBm)
Switching time	≤20 ns
On-path return loss	≥15 dB

Table 1. MMIC switch performance targets.

Figure 3. Schematic of MMIC Tx/Rx switch.

summarizes the desired switch performance.

The critical challenge of such a millimeter-wave switch is the simultaneous achievement of power handling, switching speed, and insertion loss in a form-factor tailored to today's most advanced, compact and environmentally stringent applications.

Switch architecture options

Several switch architecture options and trade offs were considered early in the design process. The most important of these were:

■ device selection: FET or PIN diode;

■ circuit configuration: series or shunt switching elements;

■ "off-state" condition: terminating or non-terminating; and

■ control circuit complexity and performance.

Device selection was a simple decision in this instance, since only PIN diodes can handle the required power levels for this application (≥ 4 W) and also provide the required insertion-loss performance (≤ 0.7 dB) at Ka-band frequencies. The disadvantage of PIN diodes is that they are current-controlled devices and, therefore, require more complex driver circuitry than voltage-controlled FETs. This was deemed an acceptable trade off, so the use of PIN diodes as the RF switch elements was finalized.

The desired SPDT switching function can be achieved with a variety of different PIN diode configurations. The three most common configurations are series diodes, shunt diodes, and a combination of series and shunt diodes. A shunt configuration was chosen for this application since it provides the required insertion loss and isolation performance. Additionally, PIN diode and other process parasitics can be readily absorbed into the circuit, and the bias network is relatively simple. To further minimize circuit complexity, a non-terminating (or "reflective") configuration was selected for this particular design. A simplified schematic of our chosen shunt diode SPDT Tx/Rx switch is shown in Figure 2.

Development approach and process selection

Different development options were reviewed—including a discrete diode switch approach, the use of existing commercially available MMIC switches, or the development of a custom MMIC switch tailored to the specific requirements of the host transceiver module. Several existing discrete diode switch designs in Endwave's product portfolio were considered, but all occupied five to 10 times the space available for this demanding application. Therefore, it was determined that a compact MMIC design was the only solution. Although there were some commercially available Ka-band switches for consideration, none were found to meet all of the performance requirements, especially for power handling. Combining available MMIC switches in parallel to meet the power-handling specification was determined to be prohibitively large, too expensive, and unnecessarily complex. Furthermore, a parallel switch approach would fall short on other key performance requirements—namely, higher insertion loss due to the associated combining network. A custom-developed MMIC switch was deemed the best solution for meeting all the performance requirements while conserving valuable circuit real estate needed for other
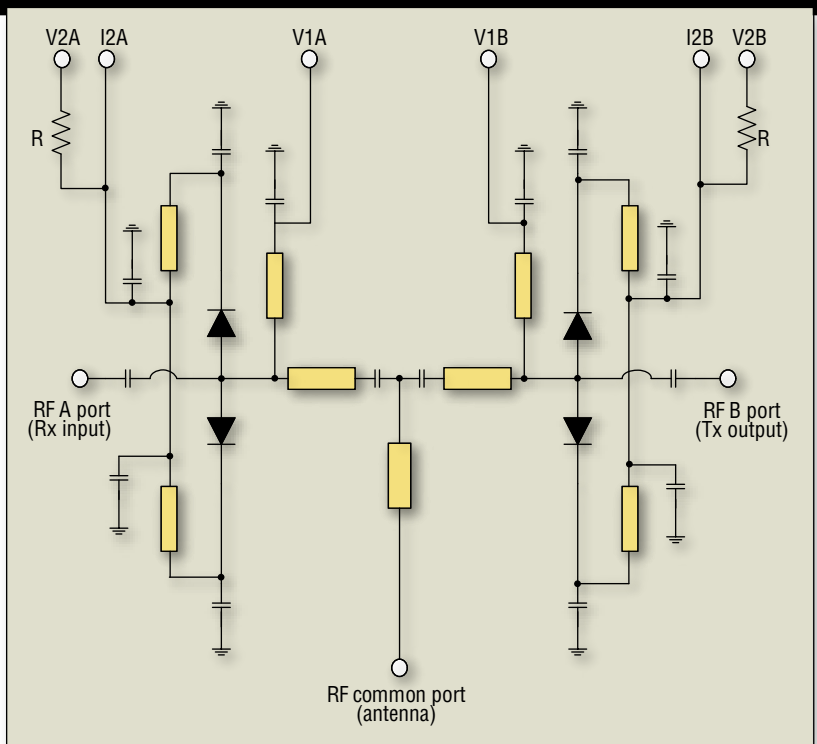
critical functions in the transceiver module.

Faced with the decision to either contract a trusted MMIC supplier to customize a chip solution, or keep the MMIC design in-house, the latter approach was chosen. The decision to take advantage of internal MMIC design resources was based on several factors, including design lead time, millimeter-wave switch design experience, and minimizing both non-recurring and recurring costs. Furthermore, with this switch deemed the critical component of the Ka-band transceiver for which it was being designed, the ability to maintain full control over the design and production of the MMIC was also a deciding factor.

The transceiver's high frequency of operation and fast switching time demanded a GaAs PIN diode process for the switch MMIC. A commercial GaAs foundry was chosen with a mature PIN diode process, validated circuit models, and an acceptable foundry lead time for the prototype wafer. The foundry GaAs PIN diode process offered a design kit with detailed models for various-sized standard PIN diode cells. The foundry process also featured MIM capacitors, air bridge metal interconnect layer, and substrate vias that were integral parts of the chosen MMIC architecture.

Design

The objective of the design effort was to optimize the switch over our narrow band of operation as a way to achieve performance better than that of commercially available broadband switches. The switch topology is fundamentally a "quarter-wavelength line/ shunt PIN diode" configuration with diodes sized for the appropriate power handling, impedance matching optimized for minimal insertion loss over the operating band, and provisions to aid integration into the higher-level transceiver subsystem design. The shunt diodes are spaced a quarter-wavelength away from the common junction. When the shunt diode on the thru path is reversed-biased, creating a high shunt resistance, the path becomes a low-loss microstrip transmission line. The transmission line impedance matching was designed to absorb the "off" state diode capacitance to achieve the optimum insertion loss and port match over the operating frequency band. On the opposite switch path, the diode is forward-biased such that it becomes a very low-resistance RF short to ground. In the isolated switch arm, the signal travels one-quarter-
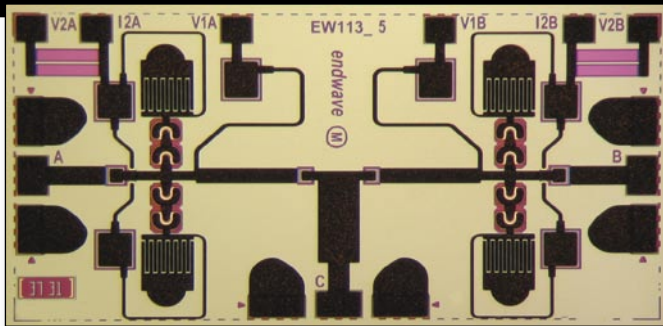
Figure 4. Ka-band Tx/Rx switch MMIC layout.

wavelength from the switch junction to the RF short. Here, it is reflected, experiencing an additional 180° phase shift. The signal then routes back through the same one-quarter-wavelength line, thus traveling a total of 360°. Through constructive interference, the reflected signal adds back at the junction so the isolated switch path does not load the "on" path of the switch.

A multisection switch using additional shunt diodes would provide increased isolation, but with the unacceptable penalty of increased insertion loss in the thru path of the switch. Rather than try to optimize one arm for increased isolation on the receive side and lower insertion loss on the transmit side, the designers chose a symmetric topology to speed development and maintain orientation flexibility in the concurrent transceiver design.

This switch was designed to control a signal level of up to 4 W in operation and survive input powers in excess of 10 W. The diode size and dc bias current were selected taking into account the diode parasitic capacitance and the foundry's published power handling limits. A larger diode provides a lower RF resistance when forward biased, but the parallel capacitance also becomes larger and provides a signal leakage path when the diode is reversed biased for high RF resistance. The switch circuit was simulated to determine the optimum diode size from performance trade offs in the low-resistance and high-resistance states. The shunt diode was configured as two separate diode legs rather than a single larger diode to maximize the heat dissipation and to minimize the via hole inductance to the ground plane on the backside of the chip.

The maximum RF power handling of the shunt PIN diode switch depends on the diode reverse breakdown voltage and its maximum power dissipation capability. In the fully reversed-biased diodes, there is negligible current flow in the high-resistance condition. For the forward-biased diodes in the low resistance condition, the voltage drop is minimal so that power dissipation is low—even though the RF current can still be substantial. To maintain linearity, as measured by signal compression, the reversed-biased "off" shunt diodes must remain off during the full swing of the RF voltage. When the RF peak voltage exceeds the reverse bias voltage of the diode, it will begin to turn "on," shunting the RF signal and leading to increased insertion loss and signal compression.

The peak RF voltage at 4 W (+36 dBm) is 20 V, assuming a 50 Ω system. This means that the reverse bias control voltage applied to the diode needs to be greater than 20 V to prevent the diode from being forward biased at the positive RF peak.

The typical microwave PIN diode processes have a nominal reverse breakdown voltage of approximately 45 V. If a reverse bias control voltage of 20 V is applied to the diode, and the switch is subjected to the maximum RF power, the total RF and dc voltage across the diode at the peak negative RF voltage peak becomes double, or 40 V. For a typical millimeter-wave diode, the linear power handling is limited by the diode reverse breakdown. Therefore, this RF SPDT switch MMIC uses a unique diode design to maximize the diode reverse breakdown voltage.
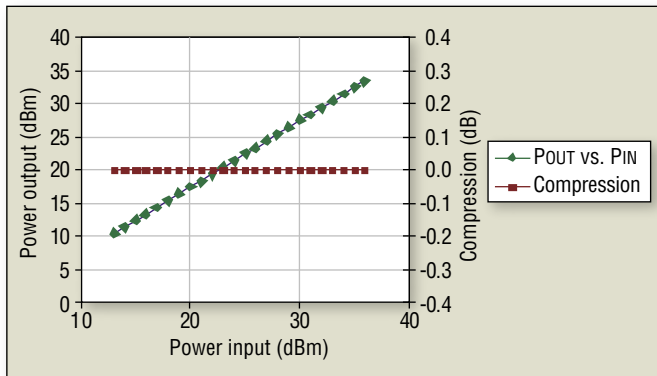
To allow system control voltage flexibility, the diode cathodes are isolated from ground by an on-chip dc blocking capacitor, as shown in Figure 3. This bias circuit topology allows the system designer to
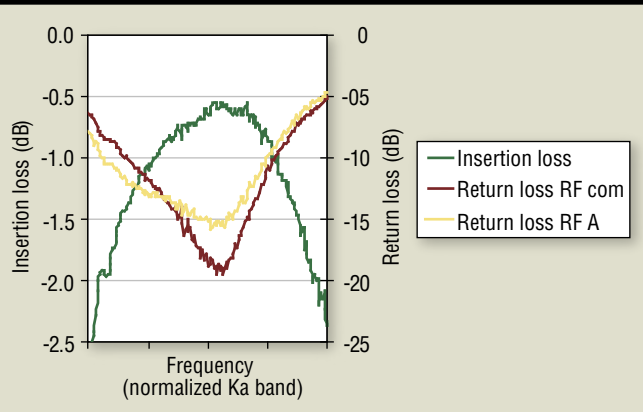
Figure 5. Measured insertion loss and return loss (on state).
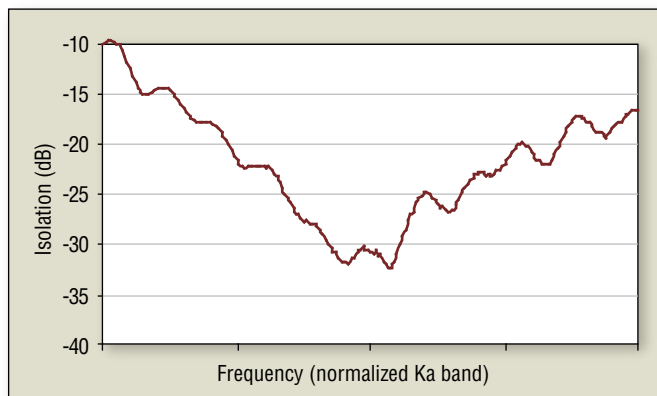
Figure 6. Measured switch isolation (off state).

Figure 7. Measured switch output power vs. input power, and compression.

maximize the reverse control voltage that can be applied to the diodes by using a combination of the available positive and negative system supply voltages. The blocking capacitor also enhances the RF design by resonating with the via inductance to create a better RF short when the diodes are forward biased.

Dc blocking capacitors were integrated into the design so no external RF components are required. In addition, the wire bond interconnects at each RF port were included in the switch simulation, so that on-chip matching could be optimized for the overall configuration within the higher-level transceiver module where the switch will reside.

Figure 4 shows a photograph of the completed Ka-band switch design. The switch was fabricated on a 4 mil thick wafer and has an overall die area of less than 3.0 mm^2.

Switch performance results

The small-signal performance of the MMIC switch was measured using RF wafer probes. The unused port was terminated by a third

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RF wafer probe with a 50 Ω load at Ka band. To approximate the true performance with bond wires, a simulated length of ribbon was added to the measured two-port S-parameters. Figure 5 shows the typical insertion loss and return loss of the switch. Measured performance meets or exceeds the goals in Table 1.

Figure 5 also shows the measured port match at the Tx port and the common (antenna) port in the low-loss switch "on" state. In the high-insertion loss switch "off" state, the measured Tx-to-Rx isolation as shown in Figure 6 exceeds the targeted 25 dB minimum isolation level over a sufficiently wide bandwidth.

For the "off" port of the switch, the measured small-signal performance closely matched the simulated performance, although the resulting isolation trace was shifted approximately 5% higher in frequency than desired. Since a well-centered design was necessary to achieve optimal performance in our narrowband application and minor discrepancies were anticipated, additional versions of the MMIC switch tuned higher and lower in frequency were included on the prototype mask to ensure first-pass success.

The input power handling of the switch was measured up to 4 W (+36 dBm) with a 30 V control voltage applied, with no observed signal compression, as evident in Figure 7. As such, the switch was shown to easily exceed the input power linear operating goal, but it has not yet been tested to its upper limit due to limitations on the output power available from the test source. However, large-signal simulations predict a 0.1 dB compression level over 6 W.

Melding circuit and system design expertise

Companies with multifaceted design teams having a diverse semiconductor and active/passive circuit design capability can leverage this experience to develop innovative multi-function RF modules. By taking advantage of internal semiconductor design expertise to customize critical components not previously available in any commercial off-the-shelf format, the PIN diode Tx/Rx switch MMIC presented here was prototyped and shows exceptional performance.

In fact, the combination of power handling, switching speed, insertion loss, and isolation of the switch exceeds the performance of any other commercially available MMIC device at Ka band. This, in turn, enabled the subsystem development team to successfully integrate the MMIC switch with surrounding components to complete the compact Ka-band transceiver module on-time, and under budget. **DE**

Authors' note

The authors acknowledge the efforts of Kevin Lynes in support of this project. Lynes assembled and tested the high-power Ka-band source and characterized the power-handling capability of the MMIC Tx/Rx switch.

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