Vol. 62 • No. 11

November 2019

Microwave Journal®

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Compact, Low Loss Switched Filter Bank Using MEMS Switches

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RF MEMS switches combine extremely low loss and high power-handling in a unique SP4T configuration, which enables the creation of miniaturized and very high performance switched filter banks (SFB).

SFBs are becoming more and more common for both commercial and military applications with the proliferation of communications frequency bands and the deployment of more frequency-agile radios. Traditional SFBs that use semiconductor devices as the switching element to select discrete filters are increasingly preferred over their electromechanical counterparts. In some applications, however, the additional losses associated with semiconductor switches is prohibitive. This is problematic when considering that at least two switches are required, at both the input and output of the filter bank, which can drive losses from switching alone to 3 to 4 dB—or higher depending on the number of filter selections and the frequency range of operation. Such losses can create significant challenges for radio designers, especially in high-power applications where 3 dB corresponds to a significant amount of power dissipation (i.e., heat) that must be managed. Recently, RF MEMS switches have become available that combine extremely low loss and high power-handling capability in a unique SP4T configuration. This enables the creation of miniaturized and high performance SFBs. This article explores the underlying technology, design approach and resulting performance.

THE GROWING NEED

RF filters are some of the most mission critical components in any wireless communications system. Smaller and lighter weight RF filters are desired to meet the demand for smaller and more capable mobile wireless communication devices whether they are used in handheld radios such as cell phones; inside a drone, an airplane, a satellite; or even on mountaintop cell towers.

The degree of rejection needed from a filter is unique to each radio, whether it is to suppress spurs or mitigate interference. This creates the need for custom filters. The significant advantages of SFBs have resulted in their widespread use in diverse applications such as radar, electronic warfare, communications and test and measurement. SFBs combine switches and filters in a single module, where a switch at the input is followed by a filter for each channel and followed by a switch at the output (see ***Figure 1***).

SFBs have significant benefits compared to approaches in which discrete switches and filters are used. The most obvious is less board space and the ease of using a single integrated module. The modules contain all or most of the components required to perform the switching function, including a microcontroller, power management and amplifiers (if required).

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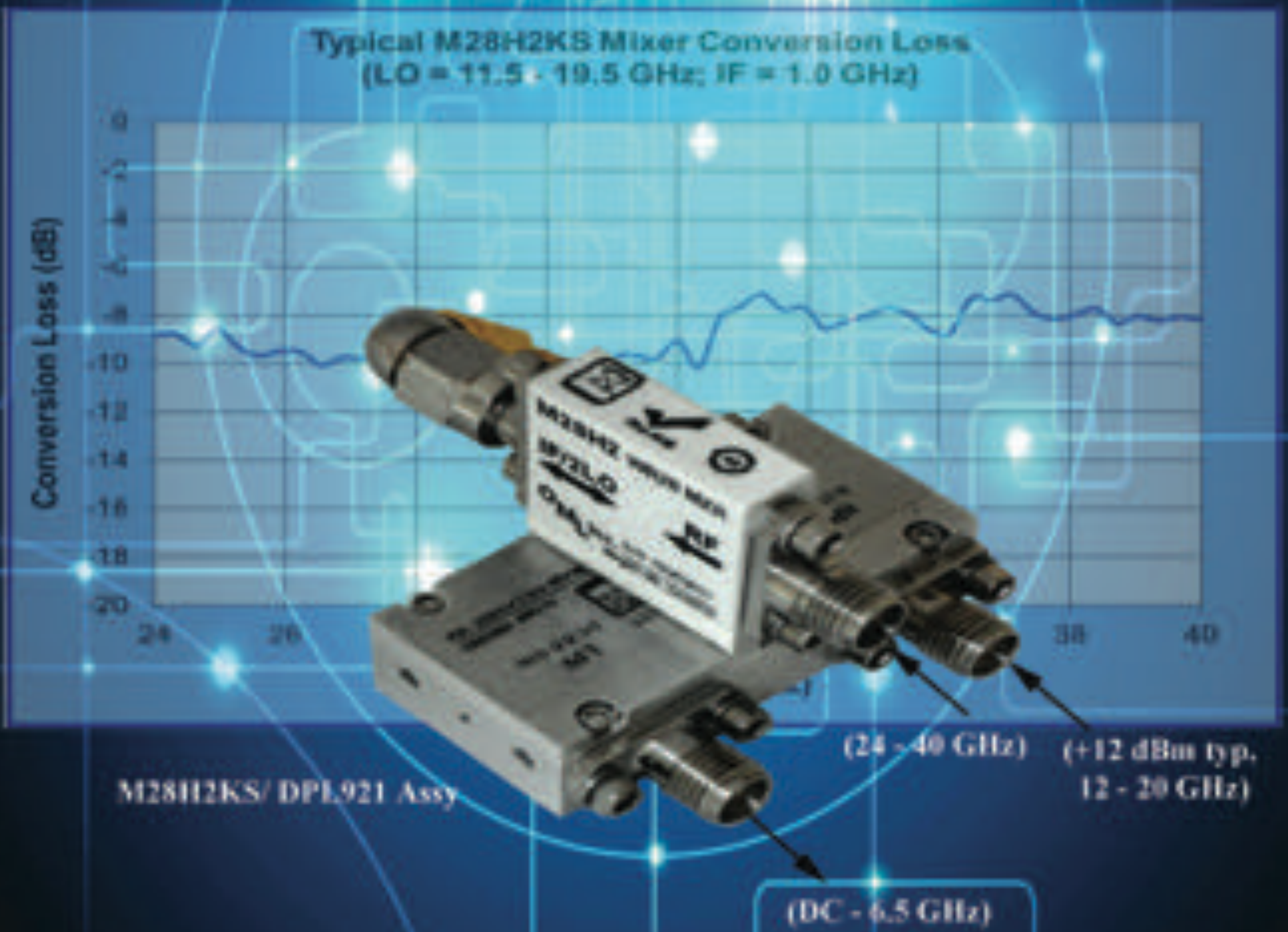

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An SFB also eliminates circuit transitions, which enables more precise impedance matching and lower insertion loss. Because the channels are internal to the module, better rejection and isolation are achieved. Any filter topology can be used based on the requirements of the application, including rejection, insertion loss and power handling.

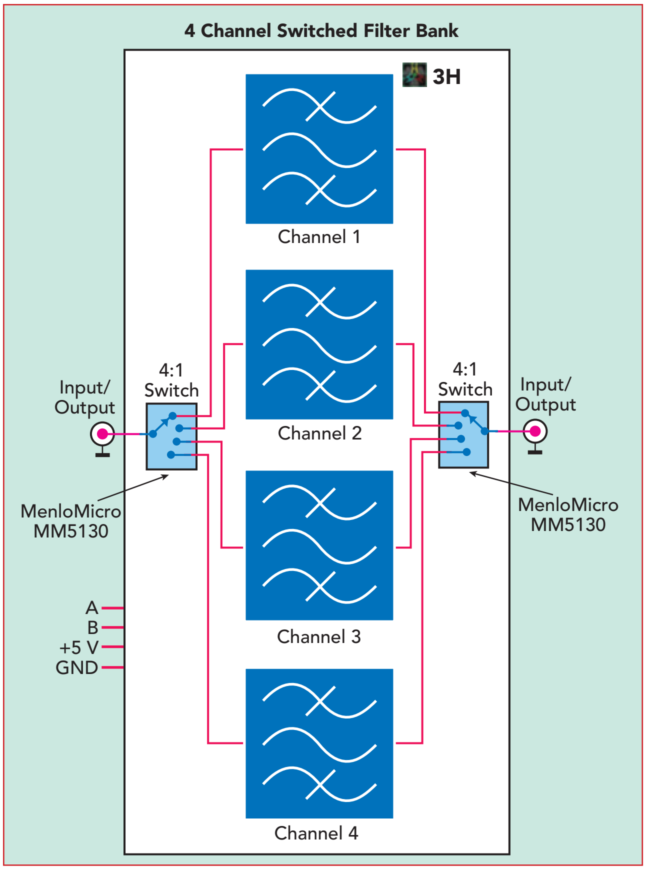


Fig. 1 **Block diagram of a 4-channel switched filter bank.**

In general, whether in the receive (Rx) or transmit (Tx) path, a key performance metric is insertion loss. To limit out-of-band interference, in receive, the SFB will usually be situated before any low noise amplifier; insertion loss from the SFB will contribute directly to the Rx system noise figure. In transmit, the SFB will be situated between the power amplifier (PA) and antenna to limit spurious and other interference from being radiated. Low insertion loss and high linearity are key to system performance; insertion loss determines radiated power, and linearity determines interference levels and receiver sensitivity. An example of a switched filter bank application is shown in ***Figure 2***.

RF MEMS SFB DESIGN

The four-channel blocking SFB shown in ***Figure 3*** uses two RF MEMS SP4T switches from Menlo Microsystems (MM5130) and four bandpass filters manufactured by 3H Communications Systems. The SFB contains all the components required to provide the drive voltages to turn on the switches, as well as a programmable microcontroller to control switching via either TTL or a PC application using USB control. The SFB measures 2.5 in. × 2.5 in. × 0.81 in. without connectors and weighs 6.5 oz. The specifications for the SFB are shown in ***Table 1***.

The RF MEMS switches are activated via electrostatic force, requiring a high-voltage source for switching. The gate bias of the switch is set at 0 VDC, which places the metal cantilever beam in a non-deflected (off) state. Thus, the path between RF input and output is isolated with an air gap, similar to a traditional mechanical relay. When the gate is set to its actuation voltage of +88 V, the electrostatic force between the gate and cantilever beam is strong enough to cause it to deflect downward, forming a connection with the contact and closing the switch. This is the deflected (on) state. For the purpose of this design, the +88 V for both SP4T switches is supplied by an Analog Devices LT3482 step-up DC/DC converter that can provide up to 90 VDC output with about 2 mA of current (see ***Figure 4***). Since the switches are electrostatic, requiring only nanoamps of current to operate, an entire switch matrix can be biased with a single boost circuit.

The output current of the LT3482 is converted to a filtered voltage through a fixed load resistor and bypass capacitor that is stable over the temperature range of the SFB. A Microchip HV513 8-channel high-

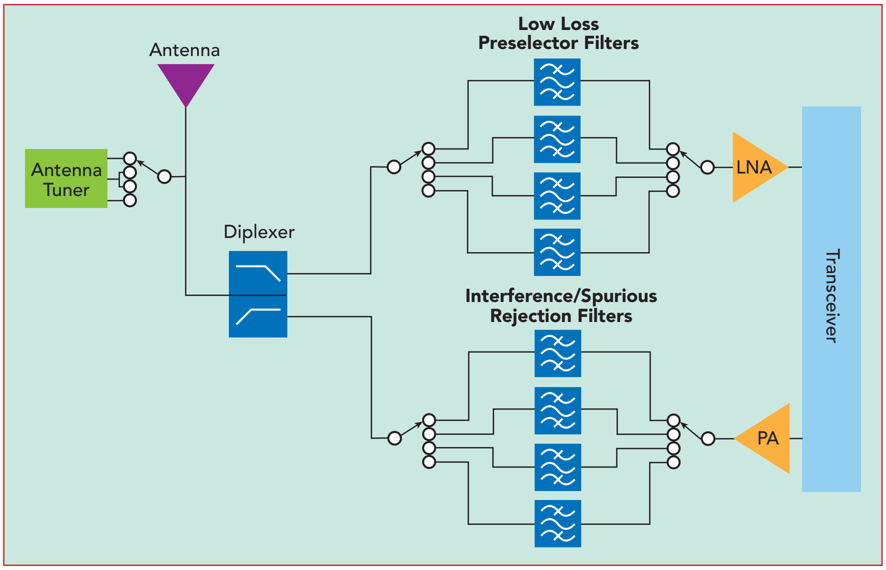


Fig. 2 **Switched filter bank use case.**

Fig. 3 **Four-channel switched filter bank with four lumped element filters and two SP4T MEMS switches.**

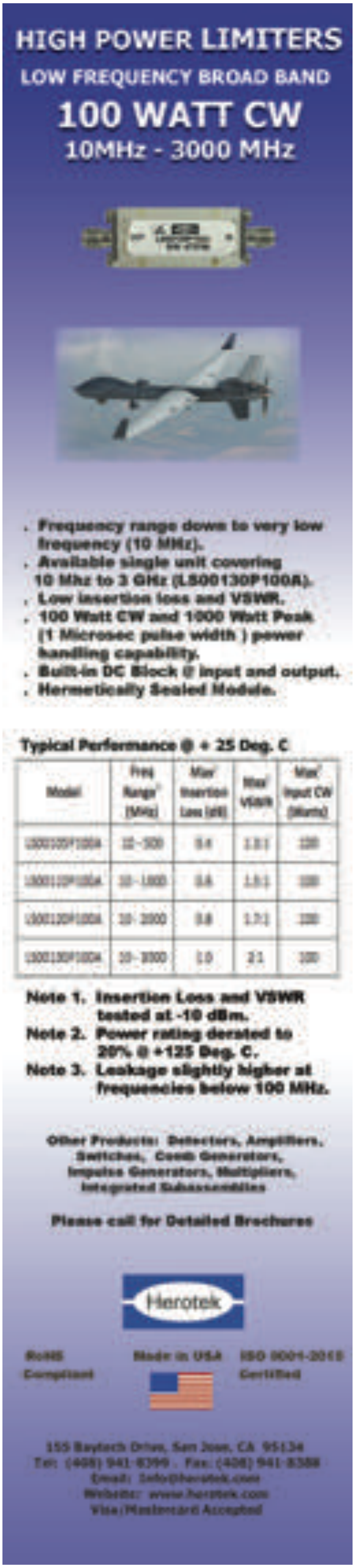


TABLE 1

RF MEMS-BASED SFB SPECIFICATIONS

Specification				
Band	1	2	3	4
Frequency Band (MHz)	740 to 1040	1676 to 2274	2970 to 3185	2525 to 2775
Insertion Loss (dB)	<2.7	<3.95	<5.2	<5.2
Rejection, Minimum (dBc)	>60	>60	>60	>60
Return Loss (dB)	>10	>10	>10	>10
Power Handling (W)	25			
Third-Order Intercept (dBm)	>85			
Control	TTL/USB			
Power Supply (VDC)	+5 V/USB			
Switching Time (us)	<10			
Current Consumption (mA)	65			
Size (mm)	63.5 (L) x 63.5 (W) x 12.7 (H)			
Operating Temperature (°C)	–40 to +85			
Vibration (10 to 500 Hz)	10G Mx			
Shock Duration	11 ms			

voltage driver routes the +88 V to each of the switch's four gate control pads. The input to the HV513 is managed by an Atmel ATSSAMD11 microcontroller, which can be controlled via USB or by direct +5 V TTL control. Other interface schemes can easily be implemented.

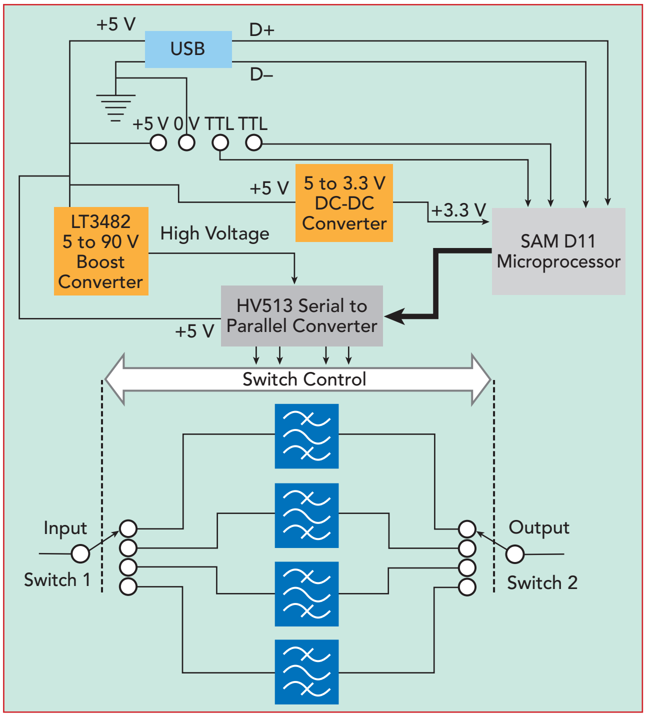
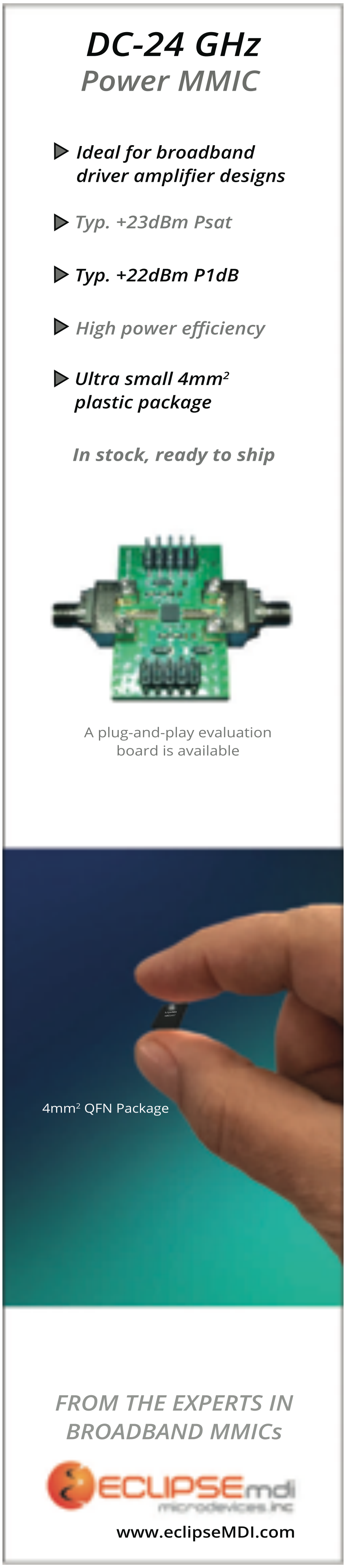


Fig. 4 **MEMS SFB control circuit.**

Layout

The input SMA connector routes the signal to the center of switch 1 (see ***Figure 5***). As the switch outputs are in the corners of the chip and need to maintain a ground-signal-ground (G-S-G) arrangement for best isolation, a grounded coplanar waveguide (GCPW) interconnection is used. This yields the best isolation while providing an optimum mounting configuration for the switch and bandpass filters. Two rows of vias are used on the ground sides of the GCPW that work to 18 GHz.

To avoid mismatch effects, sharp bends in the GCPW lines are avoided, with swept bends at least 3× the line width. As the board incorporates RF and DC components, the top layer is typically an RF material such as Rogers 4003C, especially for operation at higher frequencies; the other board layers are typically FR-4. In this design, which only operates to 4 GHz, Isola FR408HR is used for both an RF and DC substrate, since it is a more stable and high performance version of FR-4. 6 mil diameter micro-vias are used under the switch to



ensure optimum ground and maintain GCPW into the device.

Design Considerations

Depending upon the end application, it is necessary to choose a filter technology and topology to meet the minimum requirements. In this case, the filter vendor uses a proprietary technique where the filter has more zeros than poles, as opposed to traditional filter theory which requires the maximum number of zeros to be one less than the number of poles (i.e., for a n-section filter, the maximum number of zeros would be n-1). This causes the filter skirts of the passband to roll sharply, since many more zeros can be placed. As a consequence, the greater number of transmission zeros enables significantly smaller filters. These small filters used with the miniaturized, high performance RF MEMS switches reduce the size of the SFB significantly. To customize a uniquely different frequency response for each filter band, a lumped element technology with discrete zeros was chosen.

PERFORMANCE

The insertion loss meets the target requirements and is slightly better than simulated (see ***Figure 6***). The RF MEMS switch for this application adds almost negligible

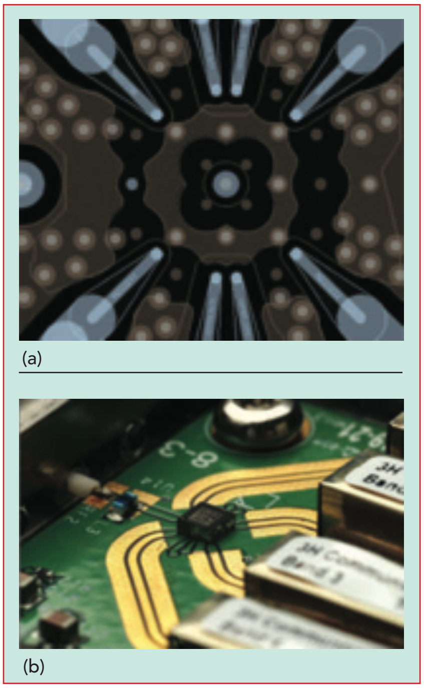


Fig. 5 **SP4T RF MEMS switch layout (a) and zoom in of trace routing to the SFB (b).**

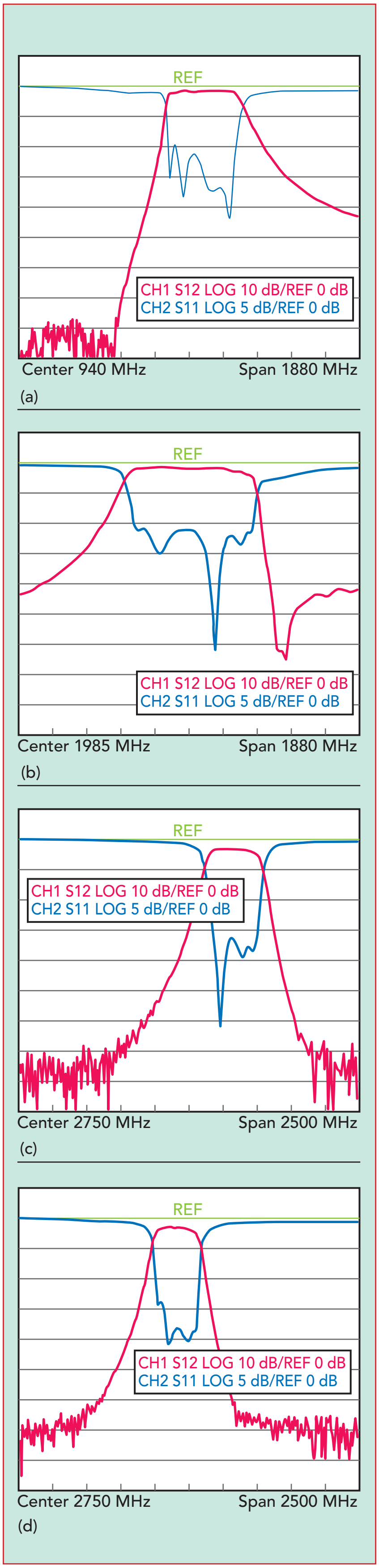


Fig. 6 **Insertion loss and return loss for all 4 SFB bands: Band 1 (a), Band 2 (b), Band 3 (c), Band 4 (d).**

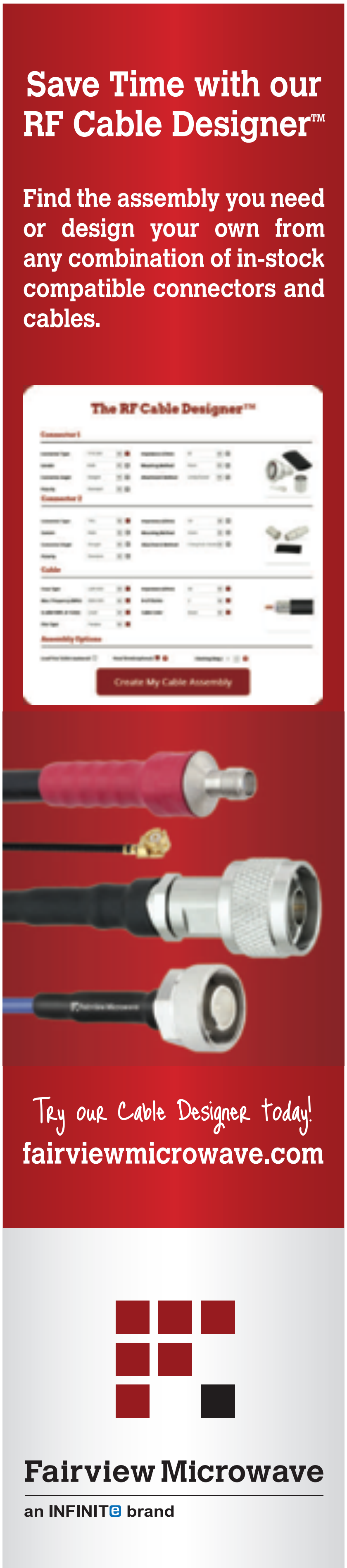
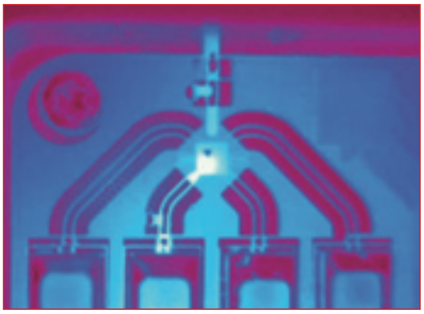


TABLE 2

HIGH-POWER RF SWITCH PERFORMANCE

Specification	PIN Diode (2 Cascaded)	GaN (2 Cascaded SPDT)	RF MEMS (MM5130)
Input Power, CW (W)	100	20	25
Insertion Loss (dB)	2 x 0.5 = 1.0	2 x 0.7 = 1.4	0.15
Switching Speed	1.5 µs	0.05 µs	10 µs
Settling Time	N/A	0.15 µs	N/A
Return Loss	15	15	20
Isolation (dB)	35	25	30
Switching Cycles	Unlimited	Unlimited	>3 billion
Third-Order Intercept (dBm)	75	60	>85
Switch Dimensions (mm)	4 x 4 x 1.5	4 x 4 x 1.4	2.5 x 2.5 x 0.9



▲ Fig. 7 **Thermal profile of RF MEMS SFB under a 25 W CW load.**

insertion loss to the overall SFB performance, using a much smaller and less complicated filter design than would normally be possible using solid-state switches.

The RF MEMS switch selected for this design exhibits a low insertion loss of 0.15 dB at 4 GHz and 0.75 dB at 12 GHz, a third-order intercept greater than 85 dBm and the capability to handle 25 W RF input power. Since it is configured as a native SP4T, there is no need to cascade switches, which can increase loss and, for high-power applications, the thermal load.

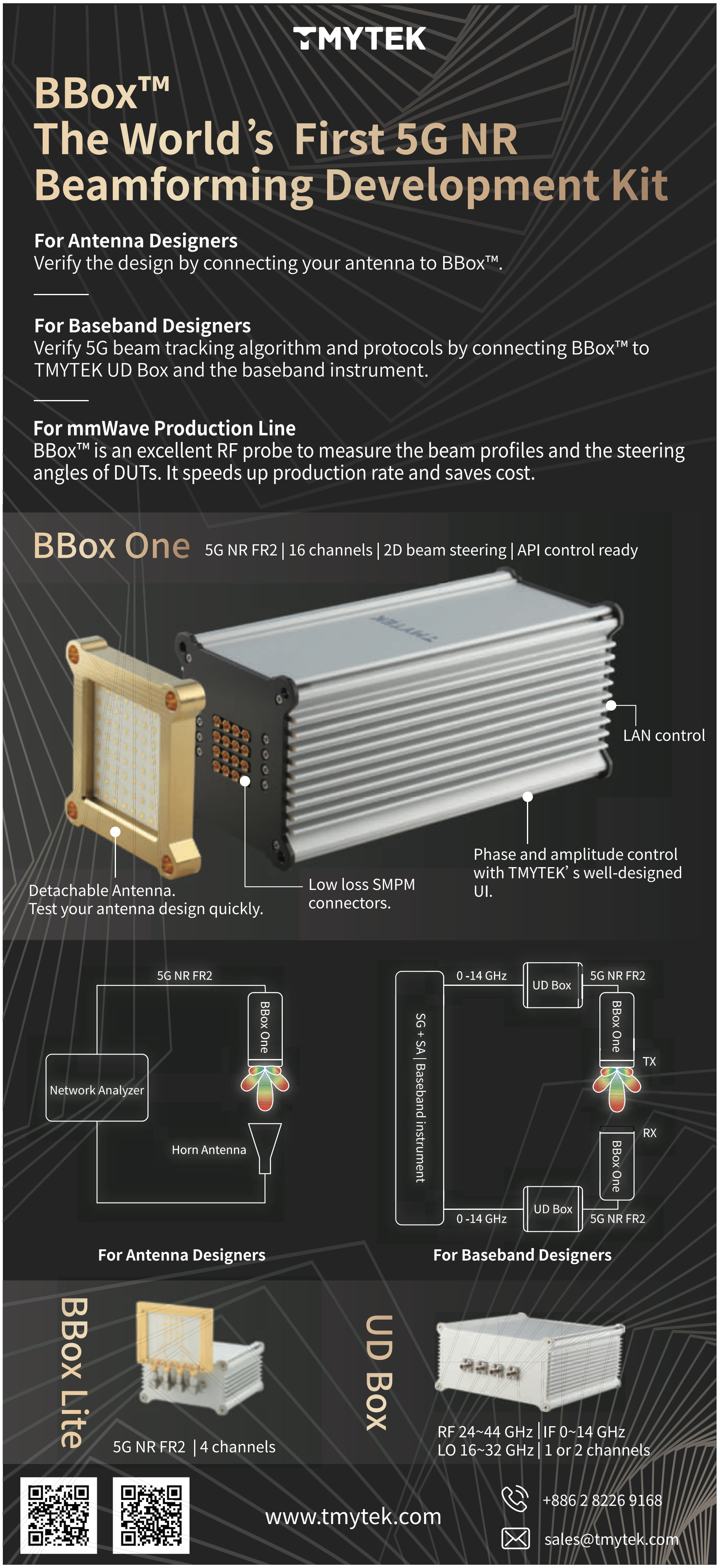
A comparison of the RF MEMS switch used in this design with traditional solid-state high-power switch technologies is shown in ***Table 2***. It is very challenging to find comparable SP4T monolithic switches that can handle greater than 20 W, so this comparison assumes the use of multiple cascaded SPDT high-power switches on both the input and output of the filters to create 1:4 multiplexing.

The RF MEMS switch used in this design is uniquely manufactured with high temperature electrodeposited metal alloys. This addresses a well-known problem experienced by many previous MEMS switches, where the switch actuator tends to deform over time and high temperature, reducing operating life. In this case, the electroplated metal alloy has a yield strength orders of magnitude greater than gold, which has been commonly used in the past for MEMS switch actuators. The results demonstrated in this SFB design show that these high temperature metal alloys are necessary to provide highly conductive and low loss signal paths and perform at elevated power levels, where some amount of self heating is inevitable. ***Figure 7*** shows a thermal image of the SFB, including the RF MEMS switch. Operating with a 10 W CW input, it exhibits only a 20°C temperature rise above ambient.

The low losses exhibited in this SFB compared to solid-state designs translate to a significantly smaller and lighter weight assembly, since heat sinks or more complicated thermal management can be reduced—even eliminated. As an example, for an SFB on the transmit path, where the radio needs to deliver 25 W to the antenna, a solid-state version would require the PA to generate an extra 2 to 2.5 dB of power into the SFB compared to the RF MEMS version. Not only does this add cost and complexity to the PA, it forces the designer to manage 10 to 14 W of extra heat in the radio.

SUMMARY AND DIRECTION

There are many ways to optimize the design. First, the high-voltage DC control section can be integrated into a single chip with minimal external passive components. There are many variants for high voltage drivers that can scale to 16, 32 or high-



er channels for applications where there are multiple SFBs to control or SFBs with more than four channels.

Additionally, the design can easily be scaled to accommodate a different number of frequency bands (i.e., more channels) and higher frequencies. For example, the SFB in this article can be increased from four to eight channels with center frequencies from DC to 18 GHz with a small penalty in insertion loss and board space. The savings in power dissipation and insertion loss for the overall SFB becomes even greater compared to solid-state when adding more channels.

Finally, there are other ways to take advantage of the extremely low $R_{on}C_{off}$ characteristics of an RF MEMS switch. The on-resistance (R_{on}) of the metal-to-metal contact is very small, typically less than 0.5 Ω, which provides the lowest possible insertion loss. The switch also has very low levels of parasitic capacitance in the off-state (C_{off}), typically less than 15 fF, providing very low signal leakage when open. These unique characteristics provide opportunities where the switch can be used to select different resonators and "actively tune" a resonator to different frequency bands, employing one or multiple switch channels to connect series or shunt elements to the resonator. This type of tunable filter is extremely challenging using solid-state switches, given the non-ideal "on" and "off" characteristics of a transistor. This is especially true for high-voltage and high-power applications that stack transistors, which can significantly degrade the resonator Q-factor. Using RF MEMS for tuning enables further reduction in space over a straight SFB while maintaining very high Q.

Designers have a variety of choices when choosing an SFB. Most of the filter characteristics are determined by the switching element as well as the filter response required by the application. The RF MEMS switch is a new entrant in this market. Owing to its inherently superior electrical characteristics, it provides an appealing alternative for many RF subsystems, especially those where reducing the SWaP are mission critical.■