Reed Relay RF Parameter Measurement

Insertion and other losses

In the past, the typical parameters used to quantify the RF performance of reed relays have been Insertion Loss, Isolation, and Return Loss (sometimes called Reflection Loss). These are frequency-related vector quantities describing the relative amount of RF power entering the relay and either being transmitted to the output or being reflected back to the source. For example, with the relay's reed switch closed and 50% power being transmitted through the relay at a particular frequency, the insertion loss would be 0.5. This is more conveniently expressed in decibels – in this case the insertion loss would be $10\log_{10}(0.5) = -3\text{dB}$. The frequency at which –3dB rolloff occurs is a convenient scalar (single valued) quantity for describing insertion loss performance.

Isolation

Similarly, the RF isolation of the reed relay can be determined by injecting an RF signal of known power amplitude with the reed switch open (coil unactivated) Sweeping the RF frequency and plotting the amount of RF energy exiting the relay allows the isolation curve to plotted. Again, plotting on a dB scale is most convenient because of the very wide range between input and output power amplitudes. At lower frequencies, the isolation may be –40dB or greater, indicating that less than 0.01% of the incident power is leaking through the relay. The isolation decreases at higher frequencies, because of capacitive leakage across the reed switch contacts.

Return Loss

Finally, return loss represents the amount of RF power being reflected back to the source with the reed switch closed, and the output terminated with a standard impedance, normally 50 ohms. If the relay was closely matched to 50 ohms at all frequencies, the reflected energy would be a very small fraction of the incident energy from low to high frequencies. In practice, return loss gradually increases (more power is reflected) as frequency increases. High return loss (low reflected energy) is desirable for high speed pulse transmission, since there is less risk of echoing signal collisions that can cause binary data corruption and increased bit error rates. Return loss is calculated from the reflection coefficient (ρ), which is the ratio of the magnitude of signal power being reflected from a closed relay to the power input, at a specified frequency.

$$\text{Return Loss (dB)} = -20 \log \rho$$

Thus, characterization of the RF performance of a reed relay involves injecting a swept frequency RF signal of known power and measuring the amount of RF energy transmitted through, or reflected back from the device under test (DUT) These measurements can be conveniently made using a Vector Network Analyzer (VNA). These test instruments comprise a unified RF sweep frequency generator and quantitative receiver/detector. In the case of a Form “A” relay, the device is treated as a network with one input and one output port, and the amount of RF energy entering and being reflected from each port is recorded as a function of frequency. Thus a complete characterization of a Form “A” relay comprises four data vectors, designated as follows:

S_{11}	power reflected from input port
S_{12}	power transmitted to input port from output port
S_{21}	power transmitted to output port from input port
S_{22}	power reflected from output port

Since a relay can be open or closed, there are 8 possible data vectors to determine. And since both magnitude and phase are involved, two data points need to be determined, a real quantity measuring magnitude and an imaginary quantity representing phase. Thus, 200-point frequency step characterization of a Form “A” relay would comprise 200 * 2 * 8 = 3200 data points.

In practice, these measurements can be simplified. First, Form “A” reed relays are mechanically and electrically symmetrical devices, so that an RF signal can be injected in either switch connection with the same (or at least very similar) results. This means that only S_{11} and S_{21} need to be recorded. Second, the measurements yielding insertion loss, isolation and return loss are simply S_{21} (switch closed), S_{21} (switch open) and S_{11} (switch closed) respectively. S_{11} with the switch open is not a particularly useful measurement, and is not included in the plots shown below. Third, for graphical representation, the magnitude and phase information at each frequency can be simply combined by computing the vector length of the magnitude and phase components from their root sum-of-squares. This simplification converts the measured S-parameters to the more familiar represen-

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tation of insertion loss, isolation and return loss.

For further information on S-parameter measurements, consult the following references, available from Hewlett Packard.

Hewlett-Packard Application Note 95-1, *"S-Parameter Techniques for Faster, More Accurate Network Design."*

Hewlett-Packard Application Note 1287-9, : *"In-Fixture Measurements UsingVector Network Analyzers"*

Hewlett-Packard, "Network Analyzer Basics", in *"1997 Back to Basics Seminar."*

Circuit simulation using S-Parameter data

Note that the complex magnitude and phase information for each S-parameter at each frequency has to be preserved if the S-parameters are to be used for modeling the relay's performance in an electric circuit. Most SPICE-type circuit simulation programs or Smith Chart graphics programs allow S-parameter data to be imported, allowing the component's electrical performance to be modeled as a "black box." On request, Coto Technology can provide the full S-parameter data for any of the relays listed below in electronic format.

Voltage Standing Wave Ratio (VSWR)

VSWR is a measurement of how much incident signal power is reflected back to the source, when an RF signal is injected into a closed relay terminated with a 50 ohm impedance. It represents the ratio of the maximum amplitude of the reflected signal envelope amplitude divided by the minimum, at a specified frequency. A VSWR of 1 indicates a perfect match between the source, relay and output load impedance, and is never achievable in practice. VSWR is conveniently calculated from the S11 parameter data using the following transformation:

$$\mathrm{VSWR} = (1+\rho)/(1-\rho)$$

Where $\rho = \mathrm{alog}_{10}(-R_{dB}/20)$
and R_{dB} = return loss at a specific frequency.

Note that network analyzers treat S_{11} reflection data as negative-signed, so that the sign needs to be changed before this transformation is applied. VSWR plots are a simple transformation of reflection data plots, they are not shown below. VSWR at any particular frequency can be converted from y-axis Return Loss using the following table:

Return Loss (dB)	VSWR
-50	1.01
-40	1.02
-30	1.07
-20	1.22
-10	1.93
-3	5.85

Rise Time

The rise time of a reed relay is the time required for its output signal to rise from 10% to 90% of its final value, when the input is changed abruptly by a step function signal. The relay can be approximated by a simple first-order low-pass filter. The rise time is approximately:

$$T_r = RC * \ln(90\%/10\%) = 2.2RC.$$

Substituting into the equation for the 50% roll-off frequency $f_{-3dB} = 1/(2\pi RC)$ yields the relationship:

$$T_r = 0.35/f_{-3dB}$$

Thus the relay's rise time can be simply estimated from the S_{21} insertion loss curve, by dividing the –3dB rolloff frequency into 0.35. For example, the B40 ball grid relay has f_{-3dB} = 11.5GHz, from which the rise time can be estimated as 30 pS.

Provided the S_{21} data is correctly compensated for the contribution of signals losses from the test fixture, this method for measuring rise time is simpler than alternative pulse injection techniques that require deconvolution of the system response time.

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The following table shows the f_{-3dB} insertion loss frequency and estimated rise time for the Coto Technology relays useful for high frequency service. These relays contain a coaxial RF shield to maintain the relay's RF impedance close to 50 ohms. With the exception of the 9852, all are Form "A" relays. The 9852 is Form "C", with both normally open (NO) and normally closed (NC) contacts. The bandwidth and rise times are listed for both 9852 contact types:

Relay Type	Leadform	f_{-3dB} (GHz)	Rise Time (pS)
9002	Through-hole	1.6	220
9202	Gull	2.0	175
9202	J	2.0	175
9290	Gull	1.25	280
9290	J	3.0	117
9402	Gull	1.25	280
9402	J	1.25	280
9802	Gull	4.7	74
9802	J	6.3	56
9802	Axial	7.1	49
9814	Gull	5.0	70
9814	J	5.8	60
9814	Axial	6.3	56
9852 NO	Gull	4.0	88
9852 NO	J	4.0	88
9852 NO	Axial	4.0	88
9852 NC	Gull	3.2	109
9852 NC	J	3.8	92
9852 NC	Axial	3.8	92
B10	Ball Grid	10.4	34
B40	Ball Grid	11.5	30

Effect of lead form on high frequency performance

Coto Technology reed relays are available with several lead form options. Surface mount (SMD) relays give better RF performance than those with through hole leads. SMD leadforms comprise gullwing, J-bend and axial forms. Each has its advantages and disadvantages, but the RF performance point of view, axial relays generally have the best RF performance in terms of signal losses, followed by J-bend and gullwing in that order. The straight-through signal path of axial relays minimizes capacitive and inductive reactance in the leads and minimizes impedance discontinuities in the relay, resulting in the highest bandwidth. However, the axial leadform requires a cavity in the user's printed circuit board to receive the body of the relay. An advantage is the effective reduced height of the axial relay, where space is at a premium.

J-bend relays provide the next-best RF performance, and have the advantages of requiring slightly less area on the PCB. The gullwing form is the most common type of SMD relay – having the longest lead length between the connection to the PCB pad and the relay body results in slightly lower RF performance than the other lead types, but initial pick-and place soldering is simple, as is rework, resulting in a broad preference for this lead type unless RF performance is critical.

Newer Leadforms

Coto Technology has developed patented new types of leadless relays with greatly enhanced RF performance. These new relays do not have traditional exposed metal leads; instead, the connection to the user's circuit board is made with ball-grid-array (BGA) attachment, so that the devices are essentially leadless. In the new BGA relays, the signal path between the BGA signal input and output is designed as a an RF transmission line, with an RF impedance close to 50 ohms throughout the relay. This is achieved using a well-matched combination of coplanar waveguide and coaxial structures with very little impedance discontinuity through the relays. These patented technological developments allow the Coto B10 and B40 reed relays to achieve bandwidths greater than 10GHz and rise times of 35 pS or less.

B40 relay interchannel crosstalk

The B40 relay contains 4 independent Form "A" channels, each having both RF coaxial shielding and magnetic shielding. The open switch RF isolation in one channel is shown in the graphs following this section. Another useful parameter for multichannel relays is the adjacent channel RF crosstalk, defined as the ratio of the signal power emitted from a closed signal channel to the input power on the adjacent closed channel. Typical crosstalk values for the B40 relay are as follows:

B40 Relay Crosstalk

Frequency (GHz)	Adjacent Channel Crosstalk (dB)
1	-67
2	-60
3	-52
4	-46
5	-40
6	-36
7	-33
8	-31
9	-29
10	-27
11	-25
12	-24
13	-21

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Skin Effect in Reed Relays

It is well known that at high frequencies, RF signals tend to travel near the surface of conductors rather than through the bulk of the material. The skin effect is exaggerated in metals with high magnetic permeability, such as the nickel-iron alloy used for reed switch blades. In a reed switch, the same metal has to carry the switched current and also respond to a magnetic closure field. A perennial question is the influence of skin effect on degradation of high frequency reed relay performance. Does increasing AC resistance at higher frequencies due to skin effect losses significantly affect insertion loss, isolation and return loss? And are there better choices for switch blade materials, or conductive surface plating techniques to reduce the effect?

The answers are: "*not significantly*", and "*possibly, but difficult to implement*." Coto Technology has run tests to determine the significance of skin effect on high frequency relay performance. Relays were made up with dummy reed switches fabricated with copper wire and other experimental materials replacing the reed switch leads. Precautions were taken to ensure that these artificial switches closely simulated the impedance environment inside the actual reed relay. When these test parts were run in comparison to a standard reed relay, the difference in measured S-parameters were generally negligible.

There are several possible reasons for this; first the increase in AC resistance due to skin effect is only proportional to the square root of frequency, whereas the losses due to increasing reactance are directly proportional to L and inversely proportional to C, and tend to override the skin effect at higher frequencies. Furthermore, the blade materials used in Coto Technology reed switches have proprietary diffused surface layers made of metals more conductive than nickel-iron, which tend to increase the conductivity near the surface. Finally, the external lead surfaces are coated with tin or solder alloys for enhanced solderability; these also help to reduce skin effect losses. Note that plating the surfaces of reed switch blades with conductive metals is not practical (except outside the glass capsule), because of problems with reduced contact force and glass-to-metal seal integrity.

The conclusion is that skin effect is as well controlled as it can be, and is not a major contributor to high frequency performance degradation under practical application conditions.

Selecting reed relays for high frequency service

The circuit designer faced with developing high speed switching circuits has several choices, including reed relays, electromechanical relays (EMR's) specifically designed for high frequency service, solid state relays (SSR's), PIN diodes and micro-electromechanical systems (MEMS) relays. In many cases, Coto Technology reed relays are an excellent choice, particularly with respect to their unrivalled RC product. RC is a figure of merit expressed in pF•ohms – where R = closed contact resistance and C = open contact capacitance. The lower this figure, the better the high frequency performance; the RC product of the B40 relay for example, is approximately 0.02 pF•ohms. The best available SSR's currently have pF•ohm products equal to about 6, almost 300 times higher; in addition, the breakdown voltage at these pF•ohm levels is far lower than that of a reed switch. The turn-off time for SSR's is also far longer than the 50 microseconds needed by a reed relay to reach its typical 10^{12} ohm off resistance. Though the drive power required by the SSR is lower than that of the reed relay, this appears to be the only general advantage; the perception of lower reliability for reed relays compared to solid state devices is largely unjustified, due to continuous technological improvements. Most Coto reed relays now have demonstrated MCBF values of several hundred million to several billion closure cycles at typical signal switching levels.

PIN diodes are occasionally considered as an alternative to reed relays for HF switching. It is difficult to find any advantages in such a choice, for several reasons; PIN diodes require relatively complex drive circuitry compared to the simple logic circuitry that can drive reed relays. PIN diodes typically have a lower frequency cut-on of about 1 MHz. In contrast, a reed relay can switch from DC to its useful cut-off frequency. In addition, the high junction capacitance of PIN diodes results in lower RF isolation than a reed relay when the PIN diode is biased "open". When biased "closed", the higher on-resistance of the PIN diode can lead to Q-factor damping in the circuit to which it is connected. Furthermore, PIN diodes can exhibit significant non-linearity, leading to gain compression, harmonic distortion and intermodulation distortion. In contrast, reed relays are inherently linear switching devices.

Electromechanical relays (EMR's) have been developed with claimed bandwidths to about 6 GHz, and isolation of about –20dB at that frequency. This isolation is

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somewhat better than that of a reed relay, since the contacts can be designed with bigger spacing than can be achieved in a reed switch, resulting in lower capacitive leakage. However, this advantage must be weighed against the increased size and cost of EMR's compared to reed relays, and lower reliability. The EMR has a complex structure with more moving parts than the simple blade flexure involved in closing a reed switch, resulting in a much lower mechanical life. If higher isolation is required with a reed relay solution, two relays can be cascaded together with a combined reliability that is still higher than that of a typical EMR.

MEMS switches (relays) are being developed based on two technologies – electrostatic closure and pulsed magnetic toggling between open and closed states. They offer potential advantages in terms of small size and low loss high frequency switching. So far however, adequate contact reliability has not been demonstrated at the switching loads required by Automated Test Equipment (ATE) applications. There are various technical reasons for this limitation that may be overcome in the future. At present though, MEMS relay technology is too immature for use in most applications addressed by reed relays. Coto Technology is monitoring these developments and may offer a MEMS solution when reliability problems are overcome.

Time Domain Reflectometry (TDR)

TDR measurements are an alternative method for displaying a relay's HF performance. They can be made be made by launching a high speed, rapid risetime pulse into a relay, and measuring the time and amplitude of the return signal. Provided the risetime of the pulse is sufficiently small, the return time can be related to the distance of an impedance discontinuity inside the relay, and the shape of the returned pulse can be used to identify whether the discontinuity is capacitive, inductive or a combination of both. Though specialized TDR equipment or oscilloscope plug-ins are available, most modern VNA's can provide TDR data by Fast Fourier Transformation (FFT) of the frequency domain reflection data. Since TDR plots do not present unique information, they are not shown in this catalog. Contact Coto Technology if you have a specific need for TDR information on any of the RF relays described in the catalog.

Relay RF Data Presentation

The data shown in the graphs following this section are derived from S-parameter measurements made using an HP 8719D Vector Network Analyzer and is presented as relative power using the transformation:

$$dB_f = 20 \log (S_{Pij}),\ i = 1 \text{ or } 2, j = 1)$$

where S_{pij} = the S-parameter polar magnitude at a particular frequency, and dBf = signal power in decibel format.

Data points are shown over a frequency range from f = 0.05 to f = 8.0 GHz except for the B10 and B40 ball-grid array relays, which are plotted from 0.05 to 13 GHz.

Insertion loss is derived from S_{21} data with the reed switch closed. Isolation is derived from S_{21} data with the reed switch open. Return loss (sometimes called reflection loss) is derived from S_{11} data with the reed switch closed.

Each data point is plotted as the polar magnitude of the real and imaginary components of the complex S-parameters recorded at each frequency step. The original full S-parameter data sets are available in complex number format on request, in Microsoft Excel or Hewlett-Packard CITIFILE format. These data sets can be imported directly into most SPICE-type circuit simulation programs, or Smith Chart display programs.

S_{11} parameters for the return loss curves were measured with the relay's reed switch closed, and the output terminated by a 50 ohm impedance load. Calibration was performed using an RF test card having a reference microstrip trace, using one-port error correction. The intention is to provide the true frequency response of the relay while eliminating spurious responses from extraneous elements such as the RF test card's microstrip transmission lines or coaxial connectors.

S_{21} data were measured with the switch open, to provide data for the RF isolation curve, or with the switch closed to provide the insertion loss curve. The network analyzer was calibrated with a full two-port method.

Since the Coto reed relays are symmetrical two-port devices, the reverse S- parameters (S_{12} and S_{22}) are

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nominally identical to the forward coefficients (S_{11} and S_{21}) and are not presented here.

Typical RF Test Card
Showing 50 ohm microstrip line connection to relay contact pins, and reference compensation trace.