Virginia Diodes, Inc.

Biasing VDI's GaAs Varactor Frequency Doublers

This document is intended to address a number of issues related to the proper application of bias to VDI's varactor frequency doublers and is a response to the many questions that our customers have asked over the years. The document covers a broad range of subjects and is intended to be comprehensive in its scope, although perhaps overly broad for any given user. The subject matter is inherently complex but the material is presented at a relatively basic level that should be readily understandable to most individuals with a basic understanding of electronics and microwave technology.

Bias Supplies

In the cases where an external bias supply is required, we use and recommend constant voltage supplies. Many common laboratory DC power supplies are suitable for this application but only under certain conditions that are explained here in some detail. Basically there are three conditions that the bias supply must meet.

1. The bias supply must be able to regulate voltage while sinking current from an active load.
2. The bias supply must be "floating". The negative bias supply terminal cannot be connected to Earth ground.
3. The bias supply must not present voltage transients to the frequency doubler.

<u>Regulating voltage while sinking current</u> - Most common laboratory DC power supplies are designed for single quadrant operation. They are capable of regulating voltages across passive loads where the supply sources current to the load. These bias supplies are not designed to sink current from an active load such as a frequency doubler. However, it is possible to use a single quadrant supply to bias VDI's frequency doublers by placing a suitable shunt resistor across the bias supply terminals. The resistor provides a shunt current path and "stiffens" the bias supply.

In the schematic shown in Fig. 1, the frequency doubler is represented by a series of diodes and R_1 is the external shunt resistor. The bias supply is attached so that the diodes are reverse biased. VDI's frequency doublers are biased through an SMA connector. The SMA center pin provides a connection to the anode and the outer conductor of the SMA provides the connection to the cathode.

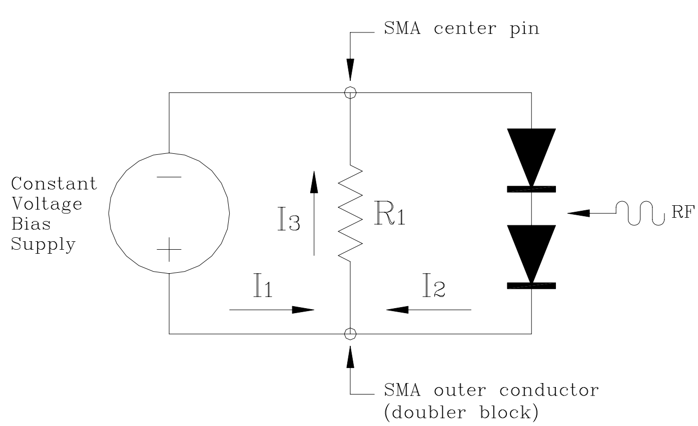

Fig. 1 - Schematic of a VDI frequency doubler, DC bias supply and a "stiffening" resistor.

When the frequency doubler is properly biased and an RF excitation is applied, the non-linear diodes convert some of the RF power to DC and generate a DC current (I_2). The current sourced by the diodes (I_2) is opposite in polarity to the current sourced by the bias supply (I_1). The shunt resistor R_1 provides a path for currents I_1 and I_2 so that they may simultaneously be positive. As long as I_1 is positive, the bias supply is able to regulate the DC voltage across the diodes. The proper value of R_1 is given by the equation $R_1 \leq V_{bias}/I_{2max}$, where I_{2max} is the maximum value of DC current that is sourced by the frequency doubler (a figure provided by VDI).

For example, assume that the desired doubler bias voltage is 12 volts and the DC current is constrained to be no more than 10 mA. The resistor value would be equal to or less than 12V/10mA = 1.2 k-Ω. If a 1 k-Ω resistor is placed across the bias supply terminals, the resistor will draw 12 mA as long as the 12 V is maintained across the terminals. With no RF power applied to the doubler, the supply sources the entire 12 mA to the resistor (I_1 = 12 mA and I_2 = 0). When RF power is applied to the doubler in such magnitude that the doubler sources the maximum 10 mA, then the supply current I_1 will drop to 2 mA and the supply is still able to source current and regulate voltage. One downside to this approach is that you are wasting power in the shunt resistor at the rate of $I_1^2R_1$ and this may be a critical concern for some applications (space platforms, etc).

<u>Floating the bias supply</u> - The SMA outer conductor is directly attached to the VDI frequency doubler block and also to the positive lead of the bias supply as explained earlier. When the frequency doubler is attached to other components in a system, the doubler block is in direct DC contact with these other system components. It is quite common for one or more of the system components to have their external cases tied to Earth ground, either directly or through a grounded DC power supply. Therefore the positive terminal of the doubler bias supply is connected to Earth ground. If the negative terminal of the doubler bias supply is also tied to Earth ground, then the bias supply terminals are shorted together. Ground loop currents may also flow through the varactors in the frequency doubler and cause permanent damage. Fortunately, most common DC lab supplies permit the user to disconnect Earth ground from the bias supply terminals. If your bias supply cannot be floated, then it cannot be used for this application.

<u>Bias Supply Transients</u> - When a DC power supply is switched on or off, transients may appear on the supply output terminals. If a particular bias supply is known to have only extremely small transients on the output terminals, then it may be powered on or off while attached to a VDI frequency doubler. However, if the transient voltages are of sufficient magnitude, they can cause avalanche breakdown of the varactor diode and thereby cause permanent damage to the diode.

For example, the breakdown voltage of the VDI model D80v2 doubler is approximately 38 V at the bias terminals. Potentials greater than 38V applied to the bias terminals of the D80v2 cause avalanche breakdown (high reverse currents in the varactor) and there is a substantial risk of permanent damage to the diode. If an extremely short duration spike of greater than 38 V occurs when the bias supply is switched on or off, then the D80v2 may be damaged if it is attached to the supply. In some cases the initial damage may be small and undetectable, but over time repeated damage may lead to noticeable degradation or even total failure of the device.

We typically use standard off-the-shelf power supplies from Agilent, Tektronix, Lambda, Keithley and other high-quality vendors to bias our frequency doublers in our lab. By observing the rules set out below we are able to avoid damage because the doublers are not attached to the bias supply when it is powered up or down. Therefore we don't really care about the transient response of these supplies. To ensure maximum protection of the frequency doublers, steps 1-4 below must be followed in order.

1. Power on the bias supply.
2. Set the supply voltage to zero
3. Connect the bias supply to the frequency doubler.
4. Ramp up the bias voltage to the desired value.

To disconnect the bias supply simply follow these steps in order.

1. Ramp down the bias voltage to zero.
2. Disconnect the bias supply from the doubler.
3. Switch the power supply off.

Electrostatic Discharge (ESD)

VDI frequency doublers employ GaAs Schottky diodes. All GaAs devices are subject to damage by electrostatic discharge (ESD). Essentially the problem occurs because the GaAs diode is extremely fast and provides the least resistance path for ESD. When you apply a DC bias voltage to the varactor, you are directly accessing the varactor diode terminals (anode and cathode) and therefore you run the risk of damaging the device if proper precautions are not observed. By using strict protocol in handling these devices as outlined in steps 1-3 below, the risk of ESD damage is significantly reduced.

1. Anyone handling a VDI frequency doubler should wear proper grounding attire (a wrist strap and/or a foot strap).
2. The work area should be well grounded. The user, device and work area should be at the same potential.
3. It is highly desirable to have the humidity level controlled. Low humidity environments tend to generate much higher levels of ESD. However, if the user is properly grounded, humidity control is not absolutely required.

Applying RF Power to the Doubler

VDI's frequency doublers are shipped with SMA shorts attached for ESD protection. If RF power is applied to the input waveguide of the frequency doubler with the SMA short attached, the varactors will be short-circuited and it won't take much RF power to generate large forward currents through the diodes. The currents will generate heat and ultimately the heat will cause permanent damage if the forward currents are sufficiently large. Therefore the frequency doubler must be properly biased before applying RF power. The following sequence must be observed.

1. Power on the bias supply.
2. Set the supply voltage to zero.
3. Connect the bias supply to the frequency doubler.
4. Ramp up the bias voltage to the desired value.
5. Apply RF power to the input waveguide of the frequency doubler.

Steps 1-5 above assume that the user is applying a constant voltage bias. There are other possible biasing scenarios where the doubler "self-biases" and an external bias supply is not used. The phenomenon of self-bias is treated in the next section.

Self-biasing

VDI's varactor doublers are capable of self-biasing across an external bias resistor over some restricted frequency range. The frequency doubler converts some of the applied RF power to DC current. This current flows through an external bias resistor and creates a self-bias voltage. Using the proper bias resistor, the doubler efficiency can be quite good and will be nearly optimal at one frequency in the band.

The current through a bias resistor peaks at one frequency and decreases at higher or lower frequencies if the applied RF power is held constant. This phenomenon is related to the frequency dependence of the diode and embedding circuit impedances and the RF reflections that result from impedance mismatches. Peak doubler efficiency occurs when the circuit embedding impedances are the conjugate of the varactor impedances at the first and second harmonics. The embedding circuit is distributed and therefore the inductive reactance of the embedding circuit tends to grow as the frequency is increased (see Foster's Reactance Theorem). The capacitive reactance of the varactor diode becomes smaller with increasing frequency ($1/j\omega c$). The trends are in opposite direction. The circuits are designed for optimal impedances near the center of the desired frequency band and the impedances degrade from the optimal as the frequency is shifted higher or lower. As the impedances degrade and the RF reflections increase, less power is coupled into the varactor and less power is converted to DC. At the higher frequencies where the DC current is zero or slightly reverse, the doublers cannot self-bias.

It is also possible to self-bias VDI's frequency doublers with an open circuit. This is equivalent to using a very high resistance bias resistor. (Make sure to remove the SMA short from the doubler!) The applied RF power generates RF currents in the diodes and a non-linear voltage waveform across the diode terminals. Since no net DC current is possible, the diode self-biases (negatively) so that the net forward current and net reverse current over one cycle are equal. The reverse leakage current is very small so only a very small excursion into forward conduction is necessary to offset this reverse current.

<u>Determination of the Self-Bias Resistance</u> - The optimal value for the bias resistor can be determined from voltage bias and DC current data. At any frequency where the DC current is non-zero, simply divide the applied voltage by the observed DC current. Replace the bias supply with this resistor, reapply the RF power and the operating point will be nearly identical.

Snap-on - There is a related "snap-on" phenomenon that may be observed when resistor biasing. At a fixed frequency, the doubler output power remains near zero as the input power is increased until a threshold input power is reached where the doubler "snaps" on and the output power rises dramatically. This phenomenon is hysteretic as the snap-on threshold is higher when the input power is ramped upward from zero and lower when the input power is ramped downward from the "on" condition. The cause is again related to impedance mismatches and RF reflections. When a diode is either open circuit or resistor biased and a small RF signal is applied, the diode RF impedance is quite large. When fully pumped, the diode RF impedance is quite low. The circuit embedding impedances are also low to optimize full-power steady-state operation. The impedance mismatch of the diode and embedding circuit at low RF power levels is very large and therefore the reflected input power is quite high (very little of the applied input power is coupled to the diode). As the RF power is increased, fractionally higher levels of the input power are coupled to the diode and the diode impedance is further reduced. This is a positive feedback scenario. The snap-on phenomenon is increasingly pronounced as the frequency is increased.

VDI attempts to tune all varactor doublers so that they may be self-biased across an external bias resistor. Operating in self-bias mode is easier for the user and also safer for the frequency doubler since the bias terminals need not be touched. However, self-bias operation provides the lowest bandwidth of any of the biasing methods we use.

In applications requiring larger bandwidth it is necessary to apply an external bias voltage. Constant voltage biasing provides increased bandwidth and greater efficiency over the band. The downside is that the user must provide a DC bias voltage to the doubler. Even greater bandwidth and efficiency are possible when the applied voltage bias is optimized at each frequency. Although this method yields the highest bandwidth it is the most difficult option for the user.

Biasing Cascaded Varactor Doublers

When several varactor doublers are cascaded to form higher-order multiplication chains, the cascaded varactors "talk" to each other. The first-stage doubler absorbs power reflected from the input terminals of the second stage doubler and this reflected power alters the first stage doubler's operating point. The magnitude and phase of the reflections are important. The reflections are minimized when both doublers are fully pumped and operating at optimal efficiency. However, in some applications our customers do not have sufficient power from their existing source to fully drive the chain. When a doubler is driven at a fraction of its designed operating power, the problems arising from reflections in the cascade are significantly increased.

Optimal bias voltages of cascaded doublers are different than those for the same doublers driven individually into a matched load. We have experimented with a number of techniques for biasing cascades. In many of the cascades we are able to use self-bias on some of the doublers, particularly those at the lower frequencies in the chain. However, we must usually employ a constant voltage bias on some of the doublers in the chain. Again, to achieve the greatest bandwidth it is often necessary to optimally bias one or more of the frequency doublers.

Biasing Distribution Systems

VDI is developing bias distribution networks that will allow our customers to provide a single supply voltage to our systems. These networks will virtually eliminate damage from ESD and will greatly simplify operation. Our customers will be notified as these networks become available.