# OCTAVE INPUT, S-TO $K_a$-BAND LARGE-SIGNAL UPPER-SIDEBAND VARACTOR UPCONVERTER

by

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Abstract

The S- to $K_a$-band varactor upconverter described herein provides significantly greater power output/bandwidth capability than obtainable from a single-sideband resistive modulator, leading to significant potential simplification in high-modulation-rate millimeter wave transmitters. This upconverter uses high quality varactors and a unique design to provide octave (2-4 GHz) instantaneous input bandwidth, and a flat (6-9 mW), 2 GHz-wide $K_a$-band output power-frequency response with minimum $K_a$-band pump power expenditure.

## Introduction

This paper describes the development* of an octave input bandwidth S-to-$K_a$-band varactor large signal upper sideband upconverter for use as a single-sideband modulator in a millimeter wave transmitter application. Resistive modulators, generally used for this purpose in the past, have proven excessively lossy and exhibited insufficient millimeter wave power output capability. As will be described herein, the considerable improvement in broadband modulation efficiency and power output capability provided by the varactor upconverter, is due primarily to the high breakdown voltage, high quality varactor(s) employed therein, and a unique broadband design procedure, whereby full octave flat-gain modulation (signal input) bandwidth was obtained under carrier (pump) power-limited operation. This enhanced power-output/bandwidth capability in turn leads to considerable potential simplification in high-modulation rate millimeter transmitters by requiring therein fewer stages of millimeter wave output power amplification.

## General Upconverter Design Considerations

Millimeter wave single-sideband power upconversion is best realized by the use of a varactor upper-sideband power upconverter in a highly nonlinear, large-signal mode of operation in which signal input (modulation) power level is of the same order of magnitude as the pump (carrier) power level and in which upconversion gain is reduced in favor of bandwidth and pump efficiency at useful output power levels. The generic varactor power USUC model, depicted in block diagram form in Figure 1, consists of the following key circuit components:

- Waveguide varactor mounting cavity, incorporating, with suitable coupling provided at the input signel ($f_s$), pump ($f_p$) and upper sideband output ("sum") ($f_u = f_p + f_s$) frequencies, and a suitable reactive termination provided at the lower-sideband, (idler) frequency ($f_i = f_p - f_s$) to prevent the flow of idler current.
- A TEM transmission line signal input circuit.
- A waveguide pump/sum matching network which is coupled to the varactor mounting cavity and, provides the desired impedance level at the varactor terminals at the pump and sum frequencies and an open circuit at the idler.
- A waveguide diplexer to separate the pump input and sum frequency upper sideband output and provide further rejection at the latter to any residual lower sideband (idler) leakage.

The general USUC configuration of Figure 1 was optimized analytically in terms of the three-frequency equivalent circuit depicted in Figure 2.

This three-frequency circuit model arises from the inter-frequency coupling generated by the nonlinear capacitance varactor junction(s) under simultaneous large signal sinusoidal drive at $f_s$, $f_p$ and $f_u$ and is characterized by complex capacitance nonlinearity factors of magnitudes $m_p$, $m_s$ and $m_u$, respectively under the open-circuited idler assumption. In the small signal limit, $m_s$ and $m_u$ approach zero, resulting in linear upper sideband upconversion gain. However, for large-signal operation, e.g., non zero $m_s$ and $m_u$, constraints on these factors impose severe limitations on $m_p$ and hence upon upconversion efficiency, particularly when traded off against input and output bandwidth.

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## USUC Design Approach

A realistic restriction on pumped large signal varactor capacitance nonlinearity factors $m_p$, $m_s$, $m_u$ which was utilized in the USUC design optimization is that given by (Reference 1):

$$m_s = m_p = \frac{2\cos^2\psi - 1}{8\cos^3\psi}$$

$$m_u = \frac{\sin\psi}{8\cos^3\psi}$$

$$\text{for } 0 \leqslant \psi \leqslant \frac{\pi}{4}$$

The above or similar formulations have been employed previously (References 1-6) in the generation of design information and performance limitations on "spot-frequency" large signal varactor USUC configurations operating under "biconjugately-matched" input and output impedance conditions, with no consideration of limitations upon and optimization of input and output bandwidth. Therefore, to enable the extension of large-signal USUC optimization techniques to large input/output bandwidths, the following design procedure was evolved for the realization of a large signal varactor USUC with wide (octave) instantaneous input/output bandwidth capability at a fixed pump frequency:

- Utilization of high cutoff frequency low-parasitic content varactor(s).
- Optimum apportionment of pump, signal and output nonlinearity coefficients ($m_p$, $m_s$, $m_u$) to maximize pump efficiency at the expense of upconversion efficiency.
- Utilization of tuned input circuit with resonance at optimum frequency $f_{so}$ to equalize upper and lower band edge output power level.
- Choice of transformed source impedance level consistent with maximum available varactor cutoff frequency to achieve flat power-output over an octave input bandwidth.
- Utilization of multiple tuned bandpass type output transformation network to achieve conjugate match to pumped varactor, over the output sum-frequency passband and pump frequency $f_p$ while providing an essentially open circuited termination to the varactor junction over the lower sideband.
- Operation in the overdriven mode to maximize $m_p$.

The power output versus bandwidth tradeoff implicit in this design approach arises from the dependence of both power output and bandwidth capability on the degree of input circuit loading, which becomes a key design variable.

## Physical Embodiment of Experimental USUC Model

The above analytical large-signal USUC design procedure formed the basis for the physical implementation of an experimental S/$K_a$-band upconverter model. This preferred configuration consisted schematically of the following, as depicted in Figure 3:

- Balanced pair of low capacitance, high quality varactors embedded in $K_a$-band waveguide, iris coupled varactor mounting cavity.
- Coaxial signal input circuit, including series tuning inductor, dual quarter wave matching transformer, RF isolated DC bias entry network, and DC blocking resonator.
- $K_a$-band waveguide pump/sum matching network, including dual quarter wave transformer and tuning and broadbanding irises.

- Four-port pump/sum circulator diplexer.
- Sum frequency multipole output bandpass filter.
- Pump level set attenuator.

The key to the successful realization of this specified large-signal USUC is the utilization of state-of-the-art high quality, low parasitic content varactors in an appropriate mounting structure. These GaAs chip varactors, fabricated in-house, exhibited nominal values of operating bias capacitance cutoff frequency of ≈ 0.1 pF and ≈ 400 GHz, reverse breakdown voltage of 15-20V and series self resonant frequency of 35-40 GHz.

The experimental S/$K_a$-band large signal USUC model was configured in accordance with Figure 3, and was packaged into a lightweight compact enclosure which included a self contained bias current meter and pump level set and bias adjustments. The final USUC package, shown in Figure 4, had dimensions of 6 x 6 x 2 in. and weighed less than 4 lbs.

### Measured Performance

The measured output power-frequency response of the experimental S/$K_a$-band USUC model, presented in Figure 5, exhibited 6 to 9 mW over the full octave (2-4 GHz) input band in an approximate three-pole equiripple response with about ± 0.9 db passband ripple, and in reasonable agreement with theory. Other aspects of measured performance included:

- Lower-sideband and pump rejection at the output port > 40 db.
- Output power variation with pump level essentially linear (1 db/db) over the 60-180 mW pump power range and at 100 mW signal input power, as shown in Figure 6.
- Output power tends to saturate at pump power levels ⩾ 200 mW (100 mW signal input), with resulting response exhibiting about 12-20 mW over the full input/output band (Figure 6).
- Output power essentially saturated with respect to signal input power at 90 mW pump level with less than 0.5 db variation at any given passband input/output frequency for input signal levels of 75-125 mW. This quality is quite useful in FM or PM transmitting systems which require minimization of residual AM.

It is felt that, with further effort in device and circuit optimizations, S/$K_a$-band USUC output power levels approaching 50 mW will be achievable over the same input/output frequency range.


### Acknowledgements

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### References


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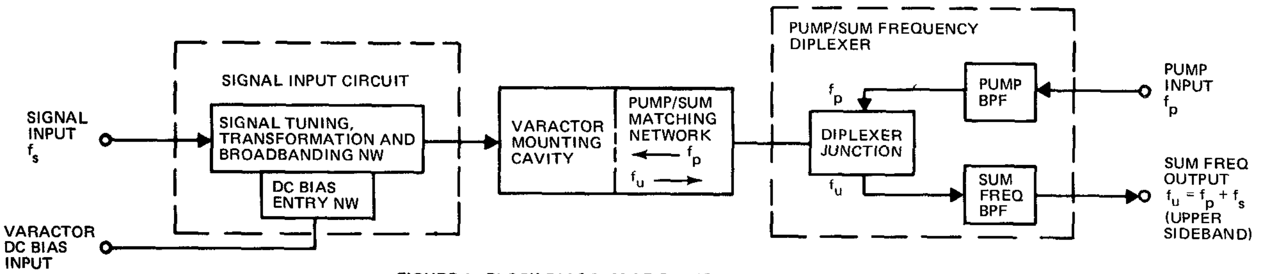



FIGURE 1. BLOCK DIAGRAM OF GENERIC VARACTOR USUC

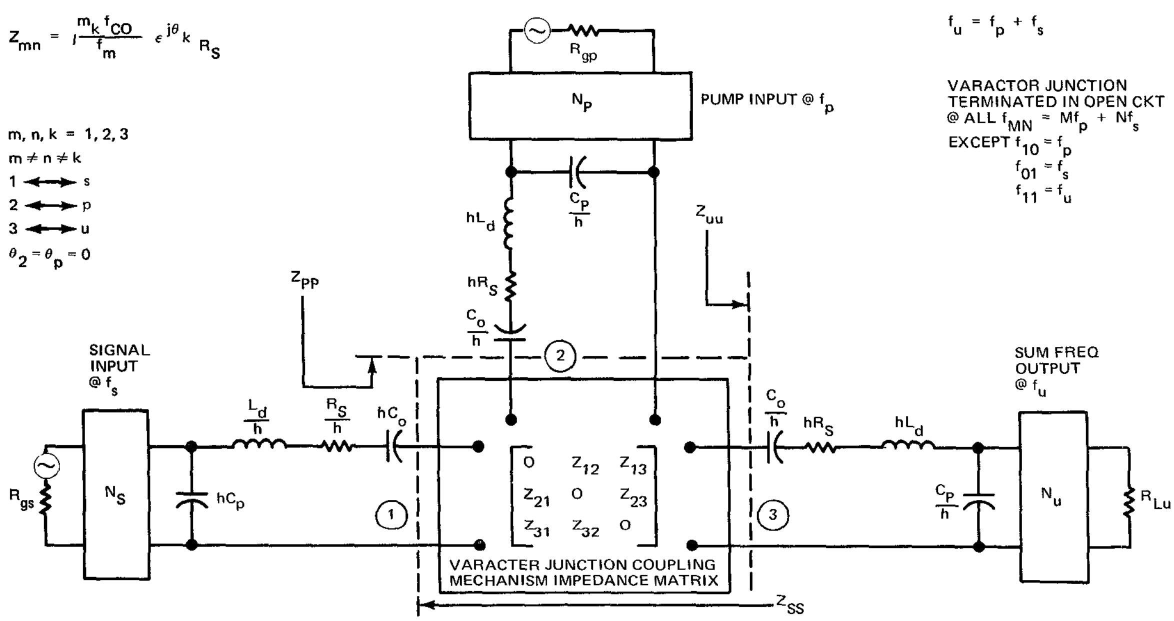



FIGURE 2. THREE-FREQUENCY VARACTOR LARGE-SIGNAL USUC CIRCUIT MODEL

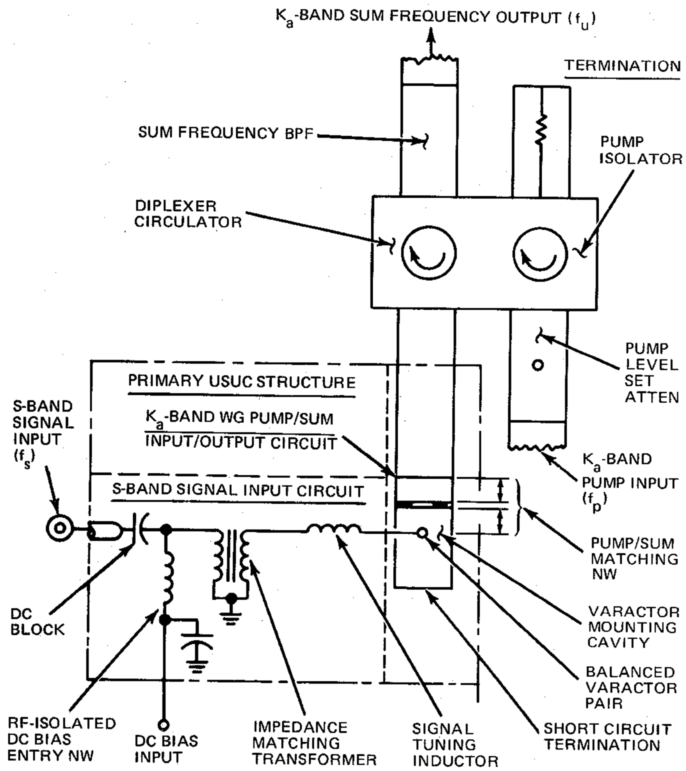
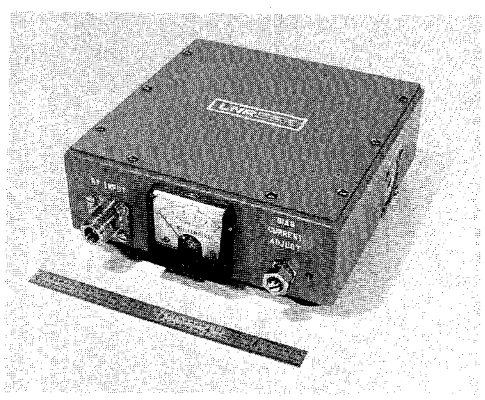
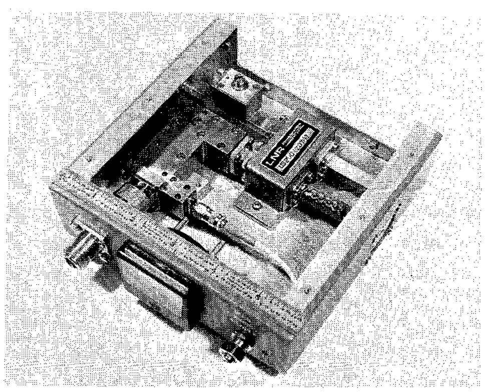



FIGURE 3. SCHEMATIC LAYOUT OF S/$K_a$-BAND USUC



A. PACKAGED UPCONVERTER



B. COVER REMOVED

FIGURE 4. PACKAGED WIDEBAND MICROWAVE-TO-MILLIMETER LARGE-SIGNAL VARACTOR UPPER SIDEBAND UPCONVERTER

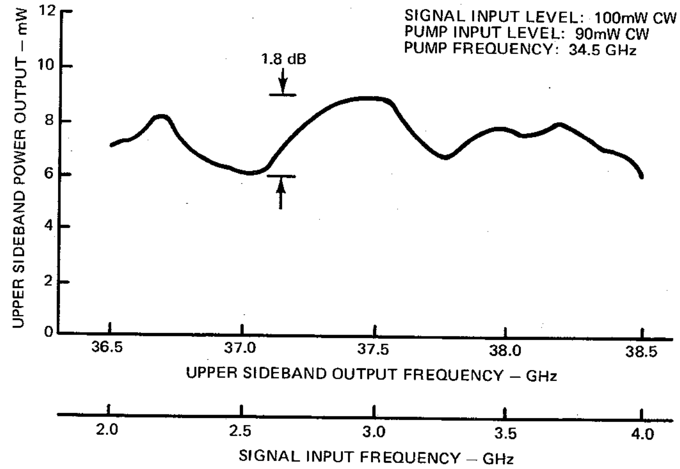



FIGURE 5. MEASURED POWER-OUTPUT-FREQUENCY RESPONSE OF EXPERIMENTAL USUC MODEL

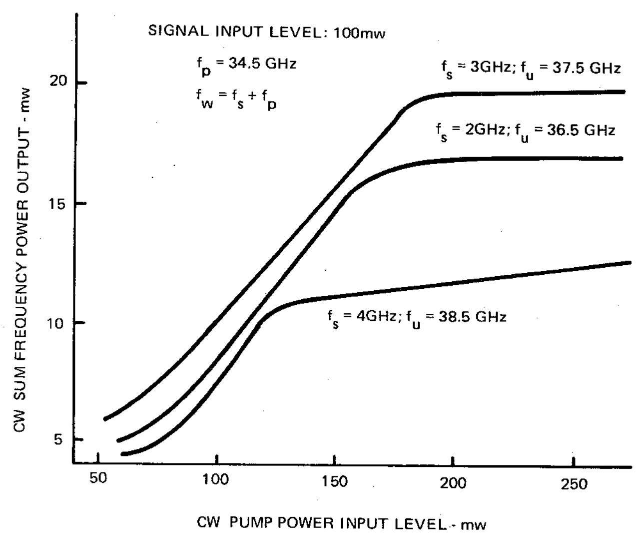



FIGURE 6 MEASURED PUMP LEVEL SENSITIVITY OF EXPERIMENTAL USUC MODEL