Microwave phase modulation using frequency multipliers

by A.Markovič, B.Schiek, H.-G.Unger

Institut für Hochfrequenztechnik
Technische Hochschule Braunschweig / Germany

For communication by radio links, satellites, waveguides etc. a pulse code modulation that is realized by phase reversal (phase shift keyed) has advantages as compared to a pulse amplitude modulation because the signal-to-noise ratio can be 6 db less for the same error probability [1]. The phase shift keying of the microwaves should be rapid (< 1 ns) and the modulation losses should be small. A suitable semiconductor element for such a phase modulator is a voltage dependent capacitance diode. A simple circuit for a reflection type modulator is obtained when the diode terminates a transmission line. Then the phase of the reflected wave can be shifted by a change of the bias voltage (figure 1a). The lossless tuner in figure 1a is adjusted so that any residual amplitude modulation is minimized. Furthermore, the tuner allows to exchange higher modulation losses for a higher phase shift and vice versa, which can be expressed by the relation [2]

$$\frac{Q}{2}\left(1 - \frac{C_{min}}{C_{max}}\right) = \frac{2r}{1 - r^2} \sin \frac{\Delta\varphi}{2} \qquad (1)$$

In (1) $Q = \frac{1}{2\pi f \cdot C_{min} \cdot R_s} = \frac{f_c}{f}$ is the quality factor of the varactor, C_{max}, C_{min} the highest and lowest capacitance value, r the magnitude of the reflection coefficient, and $\Delta\varphi$ the phase shift of the reflected wave. A practical circuit is shown in figure 1b. The characteristic impedance Z_1, which can be adjusted by exchanging the inner conductor, and the variable length ℓ_1 are represented by the tuner of figure 1a. In figure 2 the reflection coefficient is plotted in a smith chart for the varactor diode type Sylvania D 554o. Parameters are the bias voltage and input power. The measured phase variation is in good agreement with equation (1). E.g., for

f = 1o GHz, f_c = 2oo GHz, C_{min}/C_{max} = 2 and r = o,9 one gets from (1) (P_{in} = 5 mW) $\Delta\varphi$ = 64° as compared to a measured value of $\Delta\varphi$ = 6o°. With increasing input power the available C_{max}/C_{min} becomes smaller, if the varactor is not overdriven (Figure 2). Square pulses with a rise time of o,4 ns have been applied to the bias voltage of the reflection phase modulator. The phase of the reflected wave was detected by adding it via a 3 db directional coupler to a synchronous signal of the same amplitude but a constant phase. A medium switching time of 1 ns was measured for the phase shift (figure 3a). This time was found to be nearly independent of the microwave input power and bias pulse height. To this 1 ns rise time contribute both the o,4 ns rise time of the pulse generator and an unknown rise time of the detector (1 N 23 diode). In figure 3b also the measured reflection coefficient r at C_{max} and C_{min} and the phase shift $\Delta\varphi$ of the circuit of figure 1b is plotted versus the frequency. As may be noticed from figure 2 only a very small phase shift can be obtained for a higher microwave input power as long as the varactor is driven in the reverse conduction region only. The phase shift and the input power can be increased considerably when the varactor is driven into the forward conduction region. Unfortunately the switching time is of the order of the minority carrier lifetime when switching from the forward to the reverse conduction region. It looks promising, therefore to use Schottky-barrier-diodes for the phase modulator.

A greater phase shift at an even higher frequency is obtained when a frequency multiplier is combined with a reflection type phase modulator. In [3] a frequency tripler from 1o to 3o GHz has been described that has an efficiency of 3o % at an input power of 1oo mW and a 3 db-bandwidth of 3,5 % (figure 4 and 5). Since a frequency tripler also triples the phase, a 6o° phase shift at the input frequency would be sufficient to obtain a 18o° phase shift at the output frequency.

The utilization of a frequency multiplier for this purpose requires that the transient response of the multiplier is sufficiently short. A medium transient time for the phase shift of about 7 periods of the fundamental frequency has been calculated in [4] , which corresponds to a rise time of o,7 ns for an input frequency of 1o GHz. Operating the reflection phase modulator of figure 1b together with the frequency multiplier of figure 4 a switching time for the phase shift of ≈ 1,3 ns has been measured at the output frequency of the tripler (3o GHz). This switching time, however, depends upon the bandwidth of the multiplier. A decrease of the bandwidth from 3,0 to o,8 % increased the switching time from 1,3 ns to 2 ns.

In figure 5 the phase $\Delta\varphi$ of the output frequency of the tripler is plotted versus the bias voltage of the tripler varactor. It can be noticed that the phase changes nearly linearly with the bias voltage. A phase change of $9o^{o}$, for instance, can be achieved with a voltage change of 3 V. The output power then has decreased by o,6 db (fig.4). Thus the variation of the bias voltage of a frequency multiplier furnishes a simple method for phase modulation. However, to achieve a phase change of $18o^{o}$ a frequency doubler would have to be used in addition. With the method of differential-coherent phase detection a switching time of o,6 ns has been measured, while as before the rise time of the pulse generator was o,4 ns. It was found that the rise time could be minimized by properly adjusting the input frequency with respect to the frequency of maximum power output of the tripler.

With the method described in [4] the switching time of the output phase has also been calculated and was found to be 3 to 5 periods of the fundamental frequency. To obtain a quantitative expression for the phase shift $\Delta\varphi_3$ as a function of the bias voltage U_o a quadratic charge-voltage characteristic has been assumed [5] . Furthermore it was assumed that the amplitude and phase of charge components at the various harmonics as well as the impedances at these frequencies are known for the optimum efficiency and that the varactor is fully driven over the total reverse conduction region [6] . The charge components of the frequency multiplier can be described by a set of nonlinear coupled equations [6] . It is possible to find a closed form solution for the differential phase shift

$$\frac{d\varphi_3}{dU_o} / \eta = \eta_{opt} = \frac{1}{q_o\ q_1\ q_3} \left[\frac{2(q_2^{\ 2} - q_3^{\ 2})}{q_1} + q_3 - \frac{3q_2(q_1^{\ 2} - 2q_2^{\ 2} + q_3^{\ 2})}{q_1q_2 + q_2q_3 + \frac{2}{Q}(1+\frac{R_1}{R_S})} \right] \cdot \frac{1}{(U_B + \emptyset)} \qquad (2)$$

In (2) U_B is the breakdown voltage and $\emptyset$ the contact potential of the diode, $Q = f_c/f_{in}$ is the quality factor of the diode, q_o, q_1, q_2, q_3 are the normalized charge coefficients and R_1 is the optimum generator impedances. Using values for the q's and R_1 from [5] and [6] $\frac{d\varphi_3}{dU_o}$ has been plotted in figure 6 ($U_B + \emptyset$ = 2o V). For the diode of the frequency tripler (Sylvania 5o47B) $U_B + \emptyset$ was 2o V and $Q = \frac{f_c}{f_{in}} \simeq 25$ which gives a phase shift of 34°/V. This result agrees well with the measured value of 3o°/V (figure 4).

The frequency multiplier can also be used for pulse amplitude modulation. With a change of the bias voltage from the optimum value to a high negative value one can easily obtain a modulation ratio of 2o db with a rise time of o,6 ns and a decay time of o,4 ns. Again these results agree well with calculations that have been performed.

References

[1] Montgomery,G.F., Comparison of amplitude and angle modulation for narrow-band communication of binary coded messages in fluctuation noise. Proc.Inst.Radio Engr. 42 (1954), 447-454.

[2] Kindermann,H.P., Phasentastung von Mikrowellen mit Kapazitätsdioden. A.E.Ü. 21 (1967), 497-5o6.

[3] Schiek,B., Westphalen,H., Ein Frequenzvervielfacher von 1o auf 3o GHz. A.E.Ü. 21 (1967) 433-439.

[4] Schünemann,K., Schiek,B., Einschwingverhalten eines Frequenzverdreifachers. A.E.Ü. 2o (1966) 265-274.

[5] Penfield,P., Rafuse,R.P., Varactor applications. MIT Press, Cambridge, Mass. 1962.

[6] Schiek,B., Frequenzvervielfachung mit Kapazitätsdioden. Dissertation am Institut für Hochfrequenztechnik, Technische Hochschule Braunschweig, 1966.

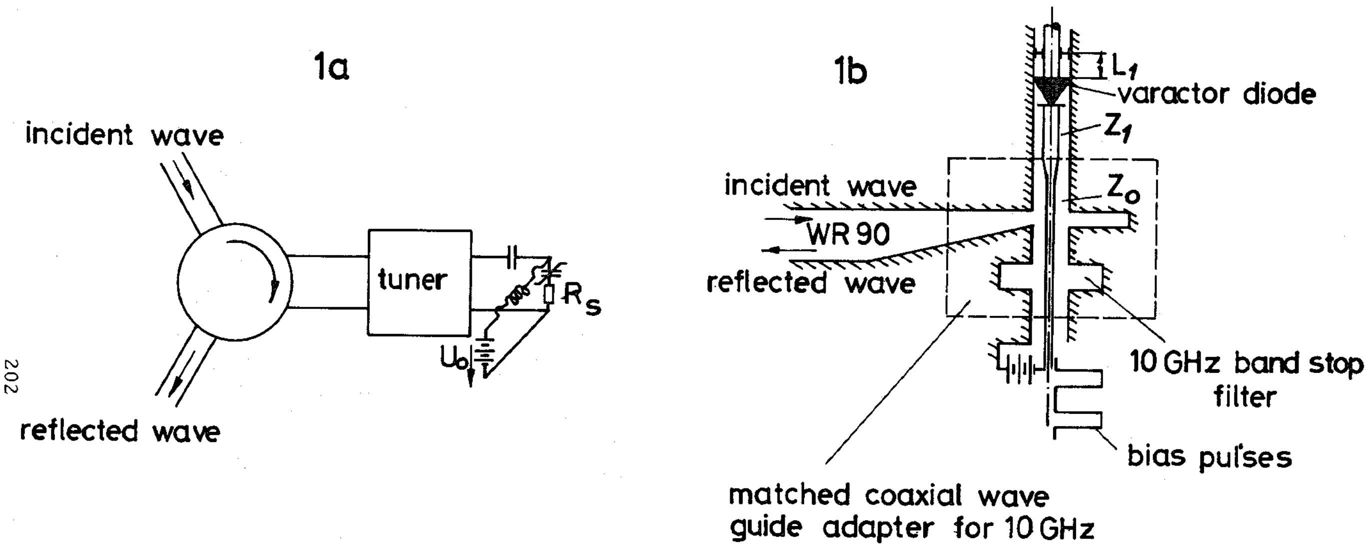


figure 1a/b Reflection type phase modulator

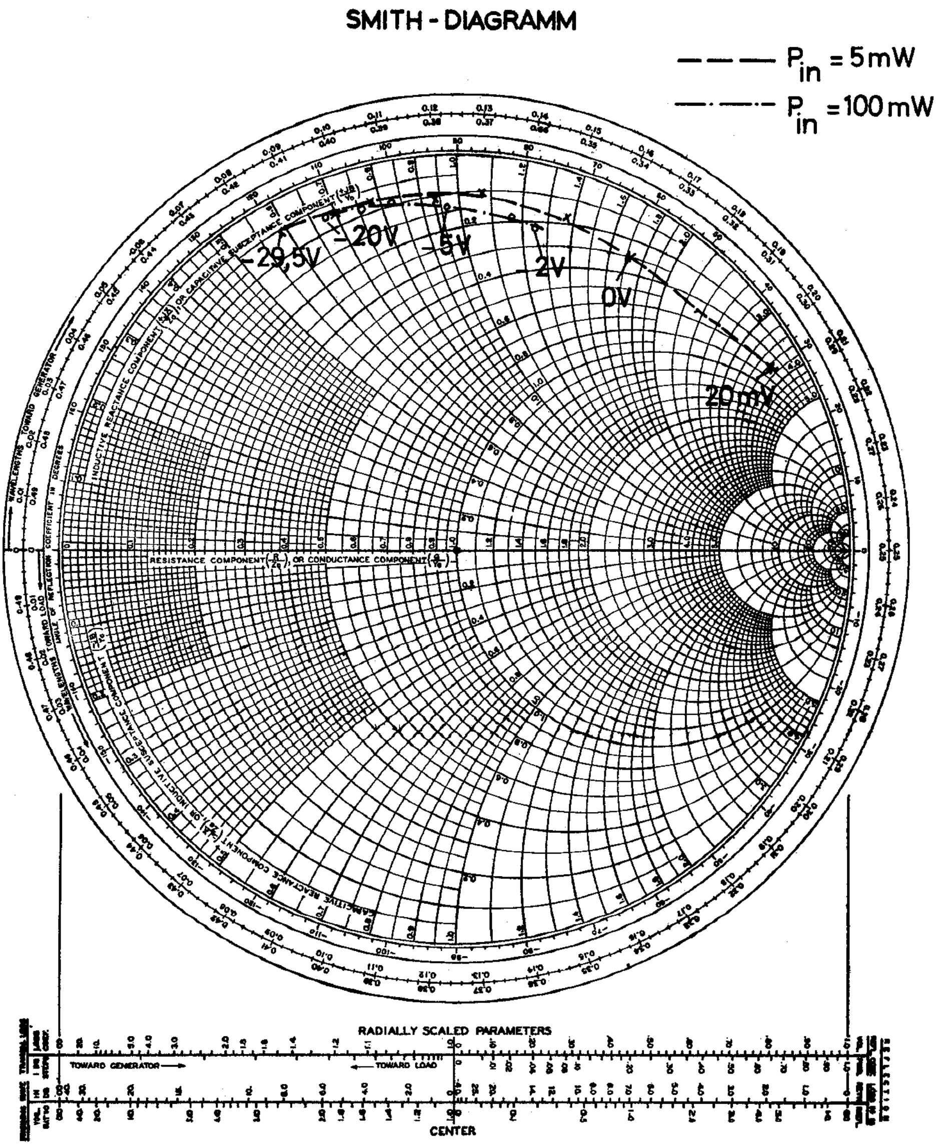


figure 2 Reflection coefficient for the diode Sylvania D554o and the phase modulation of figure 1b plotted as a function of bias voltage. P_{in} = 5 and 1oo mW. f_{in} = 9,9 GHz.

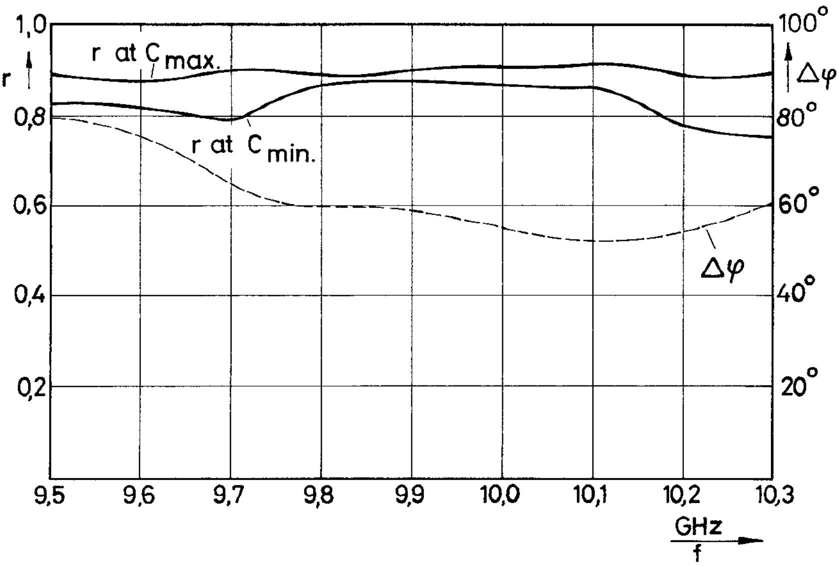
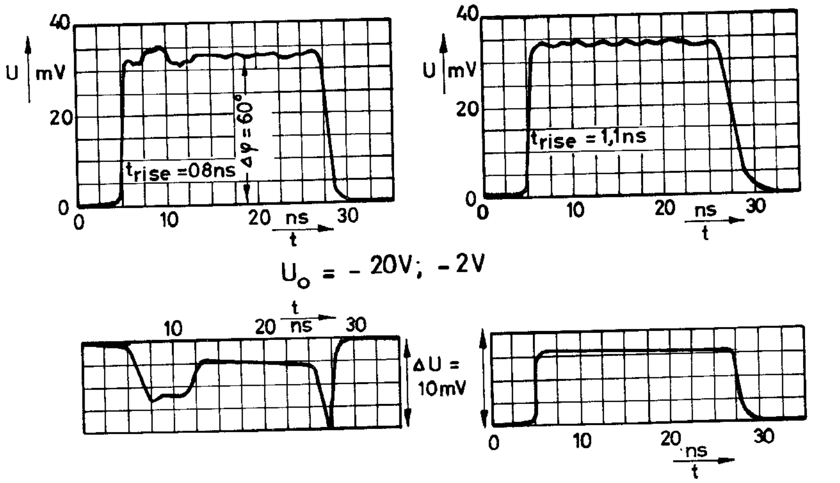


figure 3a Detector voltage for the switching of the reflection type phase modulator. Lower trace: residual amplitude modulation.



switching from C_{min} to C_{max} switching from C_{max} to C_{min}

figure 3b Reflection coefficient r and phase shift $\Delta\varphi$ of the diode Sylvania D 554o and the phase modulator of figure 1b versus frequency. P_{in} = 1oo mW

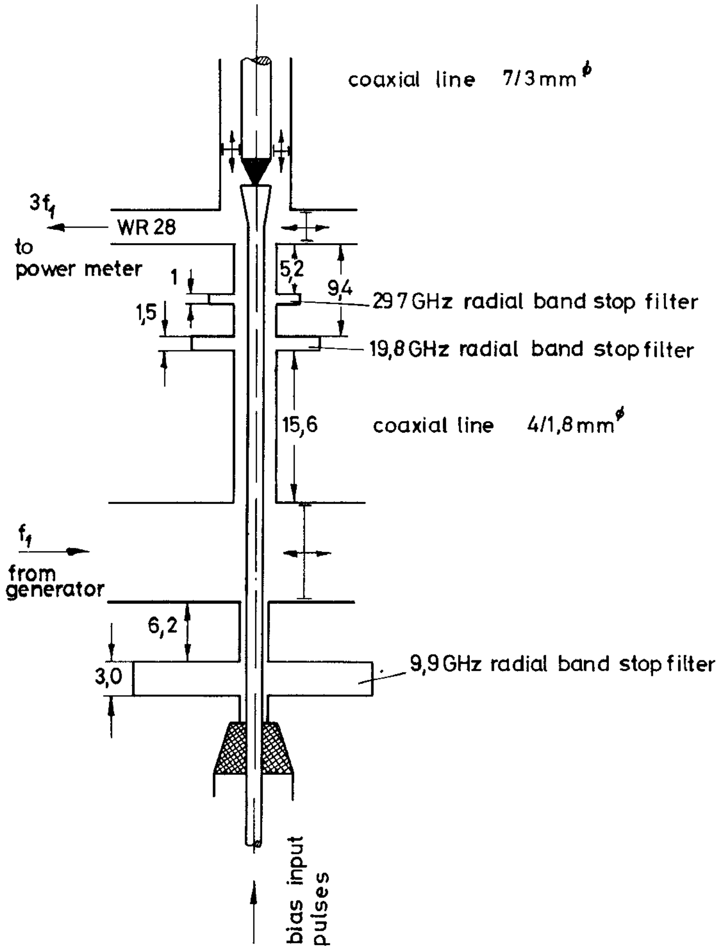


figure 4 Compact frequency tripler from 1o to 3o GHz, 3 db-bandwidth 3,5 %, 3o mW output power at 1oo mW input power. Diode Sylvania 5o47 B.

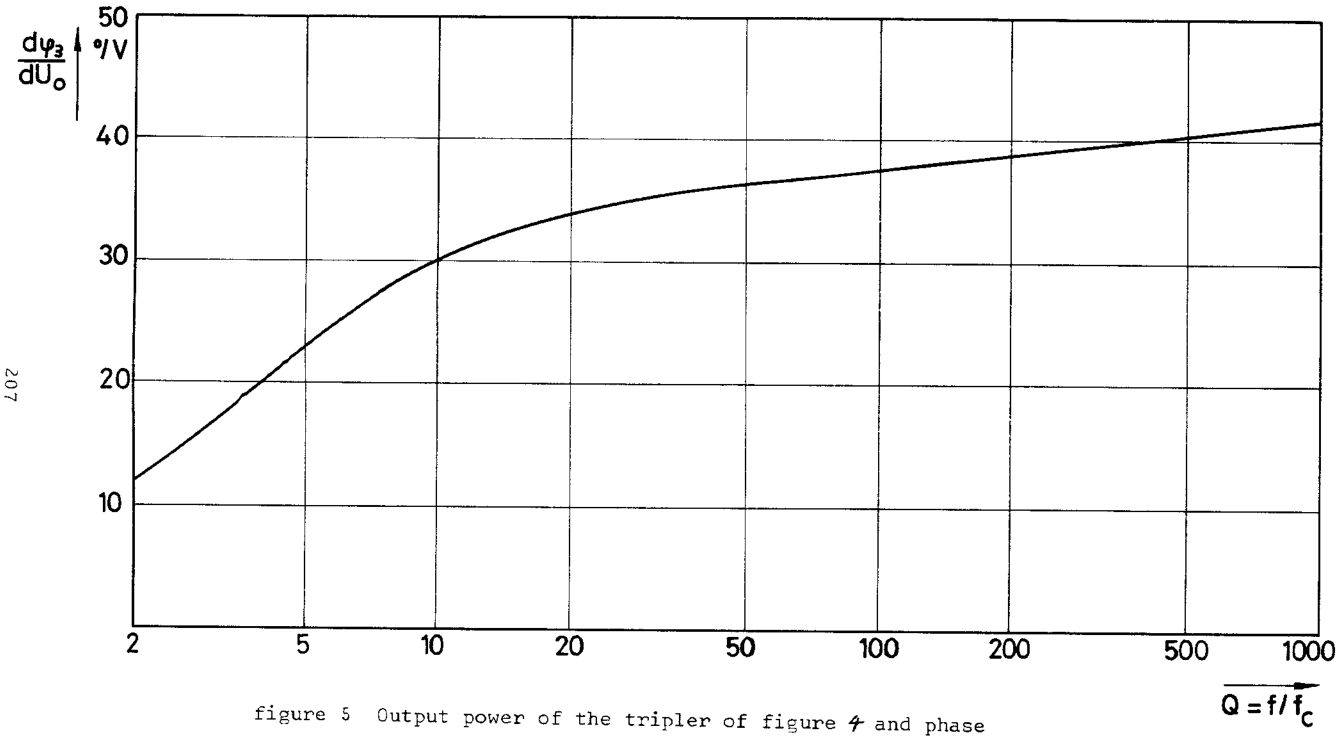


figure 5 Output power of the tripler of figure 4 and phase of the output frequency versus bias voltage.
P_{in} = 1oo mW

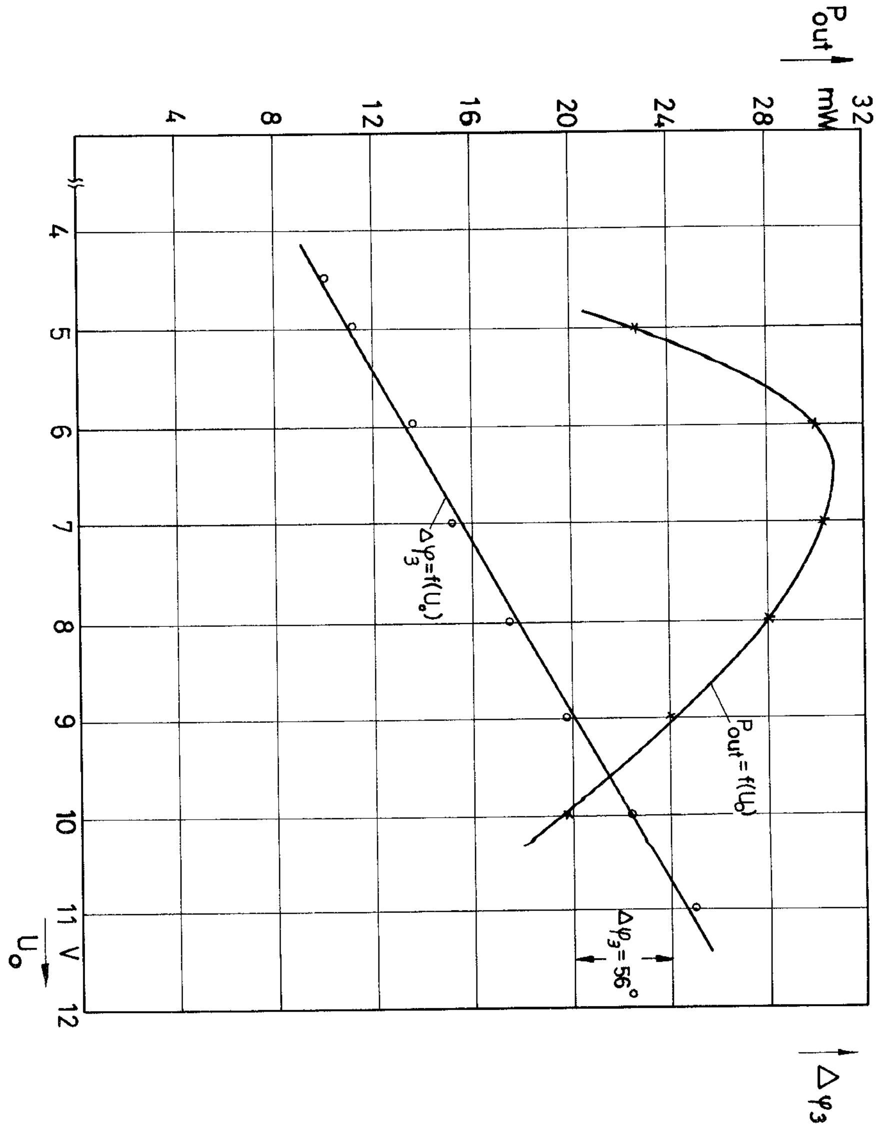


figure 6 Differential phase shift d φ_3/dU_o of a frequency tripler for the optimum efficiency as a function of the varactor quality factor as calculated from (2). $U_B + \emptyset$ = 2o V