# Effective High-Order Frequency Multipliers on IMPATT Diodes

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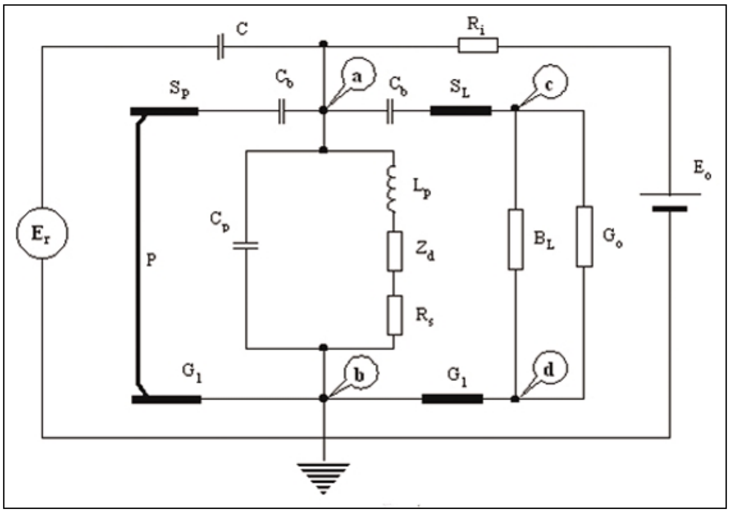
Highly stable radio frequency (RF) sources in the millimeterwave range are important for many applications. One approach uses impact ionization avalanche transit-time (IMPATT) diodes for high order multiplication of a low-frequency reference signal. This mode provides an output power level of the N-harmonic component with frequency $f = N \times F$ and $P_{out} \sim 1/N$, [1, 2]. High-order IMPATT diodes frequency multipliers are suitable as continuous wave (CW) and pulse signal sources with high phase stability and output power.



▲ **Figure 1. The multiplier's equivalent RF circuit.**

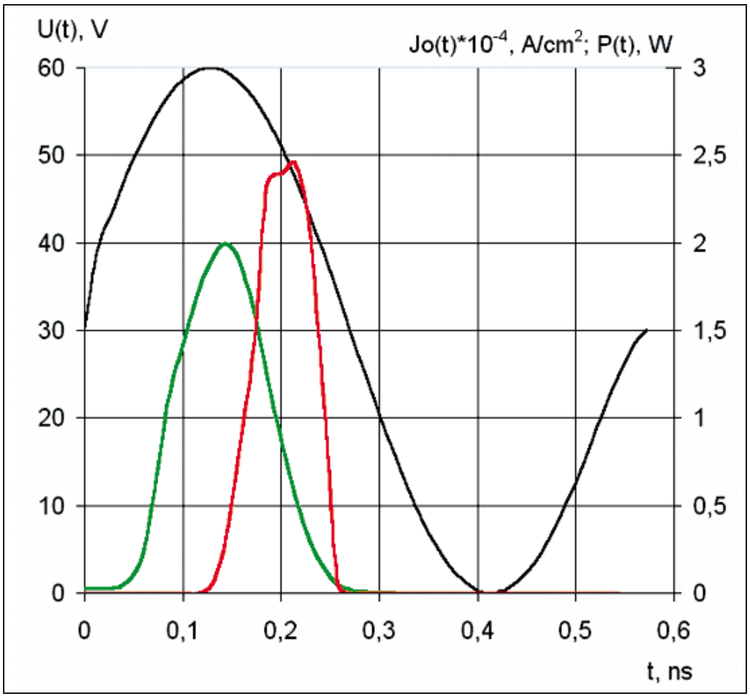
Theoretical analysis of IMPATT multipliers is based on idealized schemes of the RF circuit and on a numerical integration of an equation system defining the physical processes in IMPATT diodes with a structure $p^+ - n - n^+$ loaded by a reference signal voltage $U(t) = U_0 + U_1\sin(\Omega t)$. However, the frequency multiplication mechanism is not discussed in full measure. In the known works, it is supposed that the high nonlinearity of the IMPATT diode plays the main role in high-order frequency multiplying [2]. Methods that sharpen the current pulses passing through the IMPATT diode increase the amplitude of the high-frequency harmonic.

This article will show that high-frequency multiplication efficiency of IMPATT diodes is caused first of all by amplification mechanisms during the current pulse passing through the diode and by phase synchronization of the harmonics of the periodic current pulses sequence. In fact, this method of multiplication is radiopulsed frequency conversion on IMPATT diodes. Also described are methods for increasing the multiplying efficiency by lengthening of time of the RF amplification using low-frequency reference signals with a special waveform and the design of an optimal RF circuit for multiplication mode.

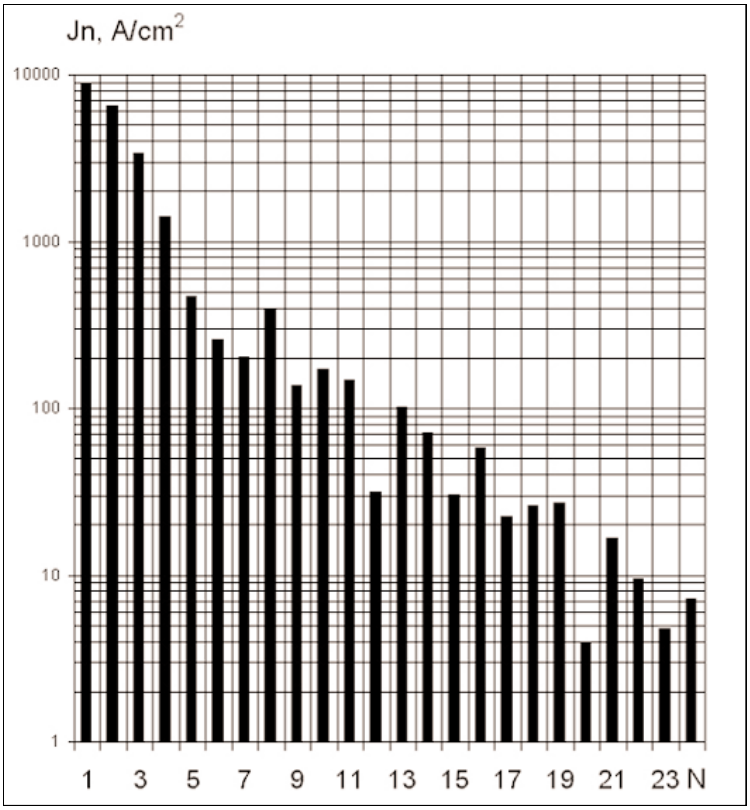
## The multiplier's equivalent RF circuit

Figure 1 shows the multiplier's equivalent RF circuit. The following designations are assumed here:

- $Z_d(\omega, I_0, U_m) = R_d(\omega, I_0, U_m) + jX_d(\omega, I_0, U_m)$ is the impedance of diode semiconductor structure;
- $\omega$ is the output operating frequency;
- $I_0$ is the diode bias current;
- $U_m$ is the RF signal amplitude;




▲ **Figure 2. The time dependences of reference signal U(t): black, diode current density $J_0(t)$: green, output power P(t): red, for multiplication factor N = 19, output frequency $f_N$ = 35 GHz and sinusoidal reference signal U(t).**




▲ **Figure 3. The spectral expansion $J_0(n)$ of periodical current density pulses $J_0(t)$ for multiplier with characteristics presented in Figure 2.**

- $C_k$ is the capacitance of the ceramic package bushing;
- $L_P$ is the package bond wire inductance;
- $R_S$ is the equivalent resistance of the semiconductor structure's heavily doped regions and parasitic resistance of the package;
- $G_1$ is the characteristic admittance of the waveguide section in which the diode is mounted;
- $G_0$ is the characteristic admittance of the output waveguide;
- $B_L$ is the reactive admittance at the output of multiplier's section;
- $E_r$ is the source of reference signal with the frequency $\Omega = 2\pi F$;
- $E_0$ is the source of the direct current (DC) bias diode current;
- $R_i$ is the inner resistance of the DC bias current source;
- $S_p$, $S_L$ are the lengths of waveguide lines from diode to sliding piston and output multiplier's section, respectfully.

The equivalent circuit shown in Figure 1 accurately models the waveguide-coaxial multiplier construction.

In the following calculations, the output frequency $f_N$ = 35 GHz. A Si IMPATT diode with $p^+ - p - n - n^+$ structure and optimum doping profile for amplification mode in the frequency range 33 to 37 GHz is considered. The lengths of the p and n layers are $l_p = l_n = 1$ μm, and the doping concentration in the p and n layers are $N_a = N_d = 3.10^{16}$ 1/cm$^3$. The impedance characteristics of this structure are defined for a wide range of voltage amplitudes ($U_m$) and bias current densities ($J_0$) [3].

### Frequency multiplication dynamic characteristics

We first consider the multiplying characteristics caused by the IMPATT diode nonlinearity, including the nonlinearity of an equivalent inductance of the diode's avalanche region $L_e \sim 1/J_0$.

Figure 2 shows the diode current density $J_o(t)$ versus time (green). This dependence is defined for the optimal diode structure, presented above, to which the voltage U(t) is applied with $U_0$ = 30 V, $U_1$ = 30 V, F = 1.75 GHz; with these values, the DC density is $J_0$ = 4, 97 kA/cm$^2$. The current pulse duration at 5 percent is $\tau 1 \approx 0, 7$ (T/2). The reference signal U(t) is shown by the black curve in Figure 2. The influence of an avalanche region inductance is a current pulse delay and in the smooth lows of current density.

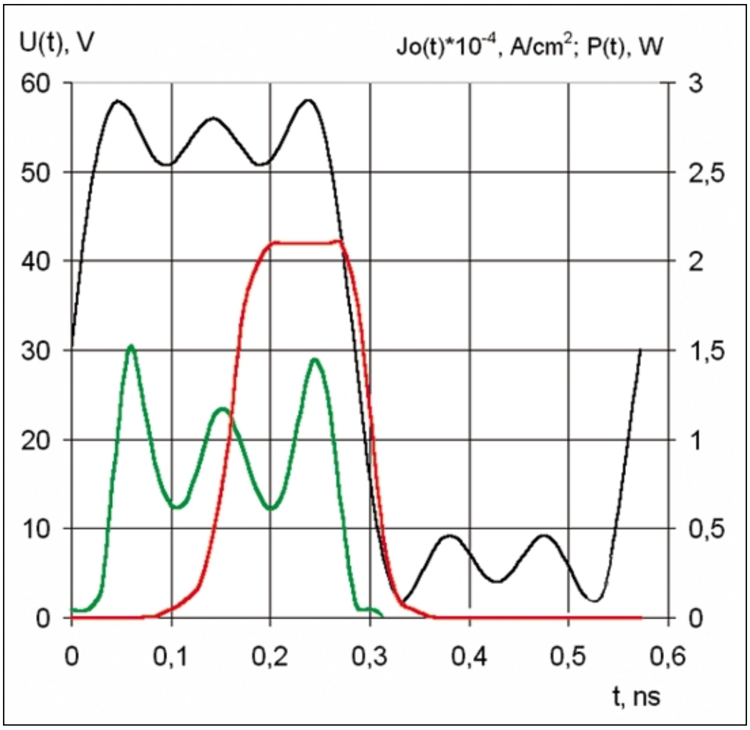
A spectral expansion $J_0(n)$ of the periodical current density pulses $J_0(t)$ is shown in Figure 3. For harmonic components with N = 19…21 at the frequency region 35 GHz, a ratio of N-th harmonic amplitude $J_N$ to maximum value of current density pulse Jm equals $J_N/J_m = 2 \times 10^{-4} \ldots 1,5 \times 10^{-5}$. If there is no avalanche region inductance ($L_e = 0$), the ratio $J_N/J_m = 0, 015$ (i.e., much larger than for the real IMPATT diode).

When current pulses $I_0(t)$ pass through the diode, the dynamic conditions are non-stationary: there are changes of RF voltage amplitude $U_m(t)$, and impedance parameters of semiconductor structure $R_d(\omega, U_m, I_0)$, $X_d(\omega, U_m, I_0)$. The following analysis assumes that interaction only takes place with the N-harmonic component $I_N(t) = I_{mN} \cos(N\Omega t)$ of current pulses because of the RF circuit selectivity. The equivalent parallel resonant circuit connected to points ab (Figure 1) at the frequency $\omega = 2\pi NF$ presents a total equivalent reactance $X_e = \omega L_p - 1/\omega C_k + X_d(\omega, U_m, I_0) + X_c$ and a total equivalent resistance $R_e = R_d(\omega, U_m, I_0) + R_s + R_L$, where $X_c$ = reactance of external circuit and $R_L$ = the load resistance recounted to the equivalent parallel resonant circuit.

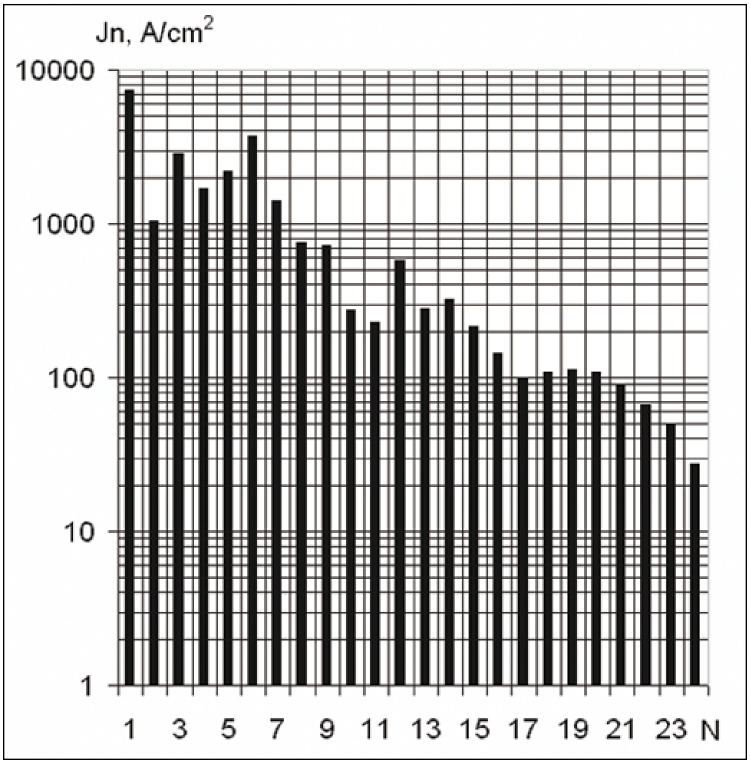
With ω far from the avalanche resonant frequency, we approximate $X_d = 1/\omega C_d$, where $C_d$ = equivalent capacitance of the semiconductor structure. Dividing the current pulse width $\tau_I$ into time intervals $\Delta\tau_{Ii}$ of minimum duration and taking into account that values $I_{0i}$, $U_{mi}$ are constant during these intervals, it is possible to calculate the time dependence of the RF current and time dependence of the output power $P_L(t)$ at frequency N × F. The values $R_d(\omega, U_m, I_0)$, $X_d(\omega, U_m, I_0)$ are defined on the basis of numerical calculations [3].

Numerical results for $P_L(t)$ for N = 19 and parameters $R_s = 0, 3\ \Omega$, $R_L = 2\ \Omega$, $L_p = 0, 16$ nH are presented in Figure 2 (red curve); $P_{Lmax}(t) = 2, 6$ W and $P_{mL} = 0.36$ W = maximum RF power during the current pulse and middle value of RF power, respectively; the DC power consumption $P_0 = 6.7$ W, the power consumption at the reference frequency $P_1 = 5.2$ W. A considerable delay of the power pulse P(t) with respect to the current pulse $I_0(t)$ takes place, as shown in Figure 2. The amplification conditions arise at $t_1$, when $R_e = 0$ and $I_0(t) = I_0(t_1)$.

With the current $I_0(t)$ increasing, the negative diode resistance increases and the growth of RF current amplitude during one period $T_N = T/19$ is defined as $I_{mei}/I_{mbi} = \exp[-\delta T_N]$, $\delta = 0.5\ R_e/L_p$; $I_{mbi}$ and $I_{mei}$ = diode's current amplitudes at the beginning and at the end of time interval $\Delta\tau_i$, respectively. At each interval $\Delta\tau_i$, the semiconductor structure amplitude $U_{mi} = Z_d(\omega, U_{mi}, I_0 i)$. $I_{mi}$ and the maximum voltage occurs at the current pulse end where $R_e$ approaches zero. The power pulse duration $\tau_p = 0.38(T/2)$ at 10 percent. The decreasing of $|R_d|$ as $U_m$ increases, peculiar for IMPATT diode, stabilizes




▲ **Figure 4. The time dependences of reference signal U(t): black, diode current density $J_0(t)$: green, output power P(t): red, for multiplier with N = 20, $f_N$ = 35 GHz and special waveform of low frequency periodical reference signal U(t).**




▲ **Figure 5. The spectral expansion $J_0(n)$ of periodical current density pulses $J_0(t)$ for multiplier with characteristics presented in Figure 4.**

the output signal power over a considerable range of N. For example, notice in Figure 2 that the diode current amplitude does not change significantly for N = 18 to N = 19.

The output power P(t) growth is restricted because of the small current pulse duration. Changing the reference waveform to increase $\tau_i$ improves the energetic performances of the frequency multiplication. The reference signal of the optimal shape is a square-wave with a pulse width equal to one half of the repetition interval T = 1/F; the maximum reference signal amplitude is defined by the permissible temperature conditions. To realize this reference signal, we can introduce additional harmonic components.

Let us consider the reference signal: $U(t) = U_0 + U_1\sin\Omega t + U_3\sin 3\Omega t + U_5\sin 5\Omega t$, where $U_0$ = 30 V, $U_1$ = 30 V, $U_3$ = 10 V, $U_5$ = 6 V, F = 1, 75 GHz; the IMPATT diode parameters are the same as in previous case and N = 20. The dependencies U(t), $I_0(t)$, P(t) are presented in Figure 4 (black, green and red, respectively). The spectral expansion $I_0(n)$ of current pulses is presented in Figure 5. The approaching of U(t) to square-wave has increased the diode current spectral components considerably; the current pulse duration is increased to $\tau_I$ = 0.9(T/2); the power pulse duration is increased to $\tau_p$ = 0.69(T/2); the maximum pulse power $P_{Lmax}$ = 2.07 W, the mean pulse power at the frequency 35 GHz $P_{mL}$ = 575 mW; the DC power $P_0$ = 6 W, the total reference signal power P1 + P3 + P5 = 4.7 W.

Achieving high-efficiency frequency conversion depends considerably on the choice of the load resistance value $R_L$. In calculations presented above, $R_L = 2\Omega$. This value is below an optimal load resistance chosen for achieving maximum power at the maximum value of a diode current. $R_L = 2\ \Omega$ is optimal for frequency conversion because an increased $R_L$ would decrease the time interval where $R_d + R_s + R_L < 0$. Decreasing $R_L$ further is restricted by the parasitic ohmic resistance $R_s$. At a fixed output signal frequency, an increased multiplying coefficient N corresponds to the increased reference signal period T, and the equivalent time duration of input signal amplification increases and the spectral harmonic degradation is compensated. This ensures that the output power slowly decreases with N in accordance with expression $P_{out} \sim 1/N$. This effect is not a peculiarity of IMPATT multipliers and is characteristic of other multiplier types.

The calculations presented here resulted in the IMPATT diodes with optimal doping profile for free-running and amplification modes. Experimentally, it can be shown that the frequency multipliers with commercial oscillator IMPATT diodes ensure effective multiplication. The optimum diode for effective multiplication with a structure of $p^+ - n - n^+$ has a doping density profile close to the profile of $p - i - n$ diodes. The doping density profile of multiplier diodes reduces the ohmic resistance in the diode structure drift region when the total voltage applied to the diode is less than the avalanche breaking point. The multiplying diode doping profile however must be fulfilled in such a way that negative resistance is not reduced considerably during the diode current pulse width. In this article, the optimization of double drift IMPATT diode doping density profile was not considered.

## Conclusion

To increase IMPATT diode frequency multiplication efficiency it is necessary to:

- Use square-wave reference voltage waveform;
- Choose the load resistance that is optimal for frequency conversion mode and that is less than an oscillator diode;
- Fulfill the optimal doping density profile of diode semiconductor structure so that the ohmic resistance of the diode structure drift region (for voltage less than breaking point) is minimal and without overly reducing the negative resistance during the current pulse.

## References

1. P. A. Rolland, et al, “Multiplication de Frequency Par Diode a Avalanche en Ondes Millimetriques,” *Acta Electronica*, Vol. 17, 1973.

2. P. A. Rolland, et al, “New Model of Operation for Avalanche IMPATT Diodes: Frequency Multiplication and Upconversion,” *IEEE Transactions MTT-24*, 1976.

3. N. P. Belousov, et al, “The Current Stabilization of Amplitude Frequency Performances of Injection-Locked IMPATT Oscillators at Temperature Range: Electronic Technique, Series 1,” *RF Electronics*, Moscow, USSR, 1989.

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