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## ELECTRONICS AND RADIO ENGINEERING

# A Device for the Formation of Short Microwave Pulses in a High Quality Factor Cavity

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**Abstract**—Microwave pulses at a frequency of 2.45 GHz with a duration of 30–55 ns (at the base level) were obtained using the effect of fast energy transfer in a pair of coupled cavities. The pulse repetition rate reached 40 kHz, and the maximum magnetic-induction amplitude was 0.32 mT at a 20-W generator power.

High quality factor (high $Q$) cavities are used in microwave engineering for producing strong fields at a limited generator power. In some applications, such as spin chemistry, the fast control of quantum states requires short microwave pulses. The high $Q$ factor of cavities prevents rapid oscillation build-up and decay; therefore, when a cavity is powered by a generator yielding pulses with short fronts, the pulse duration cannot be shorter than the double time of the transition to a steady oscillatory state. For example, for a wavelength of 10 cm and a realistically attainable loaded quality factor $Q \sim 5000$, the pulse duration is >0.5 μs.

In this work, we used an energy transfer in a pair of coupled cavities to form microwave pulses whose duration is not limited by $Q$ in a cavity [1]; this is known in the theory of electric oscillatory circuits as the effect of beats.

The device was based on two coupled cavities. One of them was connected to a microwave generator and served as a store of energy. Pulses of the microwave field were formed in the second (working) cavity. This was achieved by changing the effective length of the working cavity for a time equal to half the beat period. In this case, the maximum oscillation amplitude in the working cavity was mainly determined by the energy level stored in the storage cavity, and the pulse duration was equal to half the beat period. Separating the functions of energy storage and pulse formation between the two cavities allows one to completely utilize their useful features.

The device (whose schematic drawing is shown in Fig. 1) operates at a frequency of 2.45 GHz. Its cavities are manufactured from sections of standard rectangular waveguides. The storage cavity *1* is made of a waveguide with a cross section of $72 \times 34$ mm$^2$. It is 116 mm long and operates in the $H_{101}$ mode. The microwave power is fed to the storage cavity via a coaxial line through a coupling loop *2*.

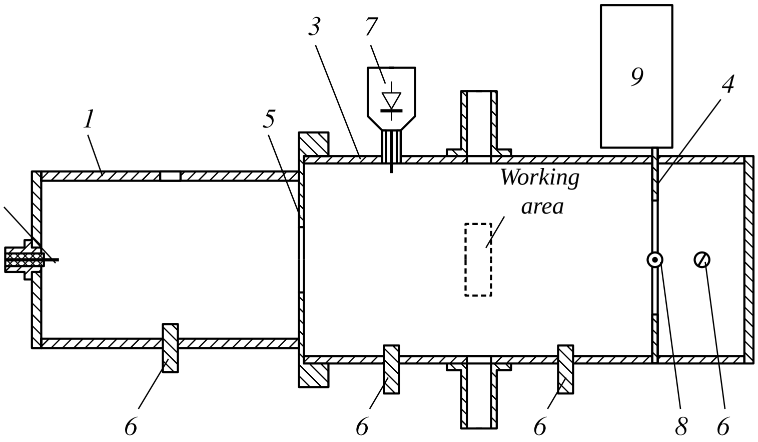

**Fig. 1.** Schematic drawing of the device: (*1*) storage cavity; (*2*) coupling loop; (*3*) working cavity; (*4*) microwave switch; (*5*) inductive diaphragm; (*6*) frequency tuning elements; (*7*) measuring probe; (*8*) *p–i–n* diodes; and (*9*) control unit.

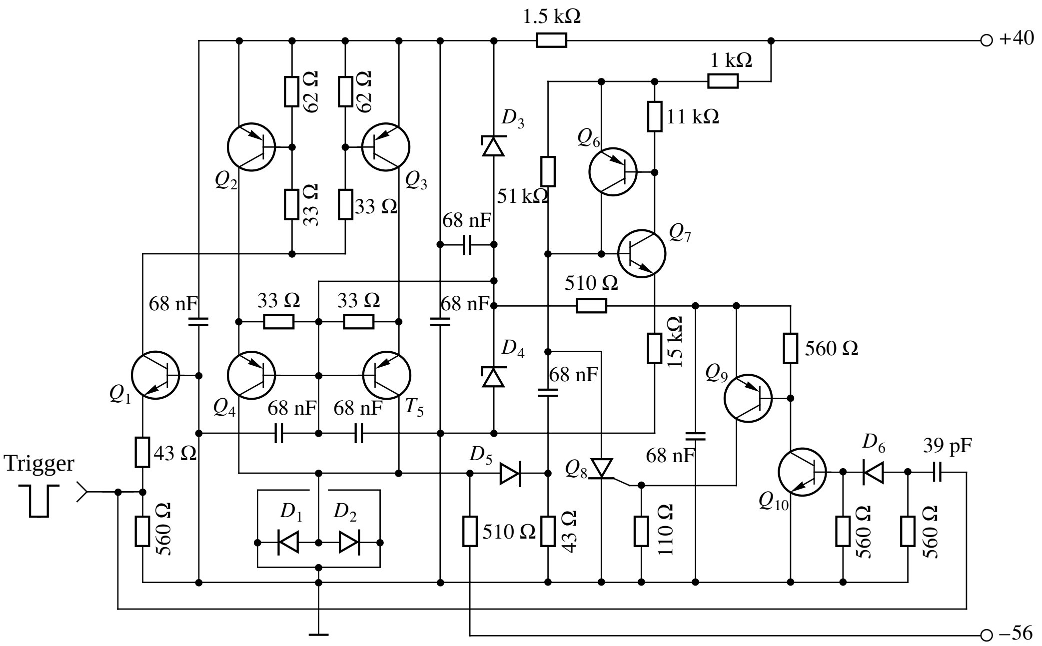

**Fig. 2.** Circuit diagram of the control unit: ($Q_1$, $Q_7$, $Q_{10}$) КТ315Г; ($Q_6$, $Q_9$) КТ361Г; ($Q_2$–$Q_5$) КТ914А; ($Q_8$) КУ112; ($D_1$, $D_2$) КА509А; ($D_3$, $D_4$) КС216; and ($D_5$, $D_6$) КД521.

Working cavity *3* is made of a waveguide with a cross section of 90 × 10 mm$^2$. Its total length is 206 mm. A microwave switch *4* is built into cavity *3* and positioned 42 mm from the cavity's rear wall. The cavities are coupled via an inductive diaphragm *5* and equipped with frequency-tuning elements *6*. The cavity design offers the possibility of mounting a measuring probe (a detector head) *7* for monitoring the envelope of microwave signals.

A resonance diaphragm with built-in *p–i–n* diodes is used as a microwave switch [2]. Two KA-509A *p–i–n* diodes *8* connected in series opposition are installed at the center of a rectangular resonance slot 52 mm wide and 1 mm high. To rapidly switch the *p–i–n* diodes from the OFF to the ON state (and vice versa), specially shaped pulses from a control unit (CU) *9* are applied to them. The CU is set up at the minimum distance from the *p–i–n* diodes in order to better reproduce the fronts of control pulses.

The device operates as follows. The operating cycle includes two stages: the storing and formation of pulses. In the energy-storing mode, the microwave generator is enabled and a blocking voltage is fed to the *p–i–n* diodes. The resonance diaphragm transmits the waves propagating in the working cavity, and the effective wavelength in the cavity ($5\lambda_g/4$, where $\lambda_g$ is the wavelength in the waveguide) is close to its total length. The oscillations in the working cavity are of minimum amplitude (the antiresonance effect [3]), and have almost no effect on the storage cavity. The latter stores an energy

$$W_1 = 2\lambda k_1 Q_1 P/[\pi c(1 + k_1)^2], \qquad (1)$$

where $\lambda$ is the wavelength, $k_1$ is the coupling coefficient between the cavity and the feed line, $Q_1$ is the loaded quality factor of the storage cavity, $P$ is the generator power, and $c$ is the velocity of light.

In the pulse-formation mode, the microwave generator is switched off, and a forward current is applied to the *p–i–n* diodes. They are enabled and short-circuit the diaphragm, which begins to reflect the waves incident on it. The effective length of the working cavity decreases to $\lambda_g$, and conditions for exciting the $H_{102}$ resonance mode arise in it. A fast energy transfer from the storage to the working resonator is initiated. When all of the energy stored in it is transferred (minus losses) to the working cavity, a reverse-transfer process begins.

If the moment of switching the *p–i–n* diodes is taken for the reference point and the initial oscillation amplitude in the working cavity is ignored, the energy stored in it then has the following time dependence:

$$W_2(t) = (\pi^2 c^2 k^2 W_1/(\lambda^2\Omega^2))\exp(-2t/\tau)\sin^2(\Omega t), \qquad (2)$$

where $k$ is the coupling coefficient between the cavities, $\tau$ is the time constant of the transient process, and $\Omega$ is the beat frequency,

The parameters of the transient process can be expressed through the cavity characteristics

$$\tau = (\pi c/(2\lambda))(1/Q_1 + 1/Q_2),$$

$$\Omega = (\pi c/(2\lambda))\sqrt{4k^2 - (1/Q_1 - 1/Q_2)^2},$$

where $Q_2$ is the quality factor of the working cavity.

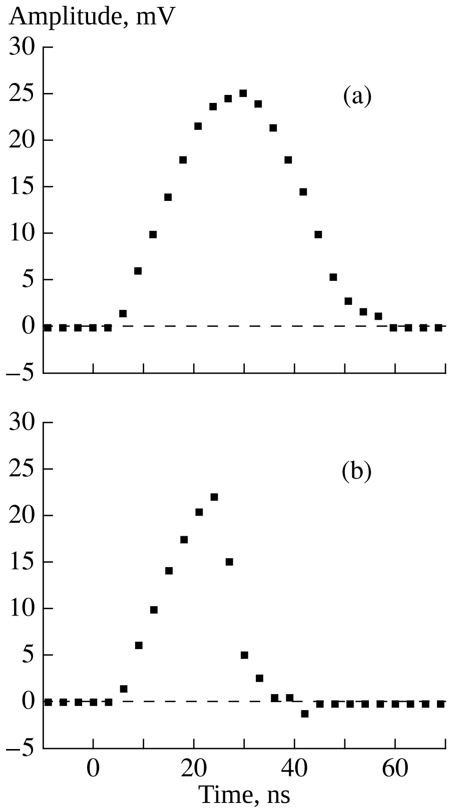

**Fig. 3.** Oscillograms of microwave pulses in the working cavity (signals from the detector head) at a trigger-pulse duration of (a) 40 and (b) 10 ns.

At the moment $\pi/\Omega$, when all of the energy leaves the working cavity, a blocking voltage is fed to the *p–i–n* diodes, and the energy-transfer process terminates. Thus, a microwave pulse with a duration $T_p = \pi/\Omega$ (at the base level) forms in the working cavity. The pulse envelope is determined by expression (2).

During the reverse energy transfer, antiphase oscillations (as compared to those from the generator) appear in the storage cavity. Therefore, delaying the generator disabling moment slightly retards the reverse energy transfer. Experiments have shown that this insignificantly affects the pulse profile and duration.

Note that, when the operating modes are switched, the standing wave shifts along the working cavity by $\lambda_g/4$. As a result, the working region located at the maximum of the magnetic field in the pulse-formation mode turns out to be at the minimum of the magnetic field in the energy-storing mode. This additionally lowers the magnetic field value in the working region during the intervals between microwave pulses.

Using the expressions for the components of the magnetic field in a rectangular cavity [3], we can calculate the amplitude of the magnetic induction in the working cavity:

$$B = \frac{4}{c(1+k_1)}\sqrt{\eta z_0 k_1 Q_1 P/(\pi a b \gamma^3)}, \qquad (3)$$

where $\eta$ is the fraction of the stored energy transferred to the working cavity, $z_0$ is the characteristic impedance of the vacuum, $a$ and $b$ are the transverse dimensions of the working cavity, and $\gamma = \lambda_g/\lambda$.

In the energy-storing mode, the field structure in the working cavity is such that the microwave switch is at the electric-field maximum. Expressions (1) and (3) are valid as long as the amplitude of the microwave voltage across the *p–i–n* diodes is below the double blocking voltage. At a higher microwave voltage, the loss in the *p–i–n* diodes abruptly grows and a further increase in the generator power does not lead to an appreciable increase in the stored energy and the magnetic induction amplitude. Measurements have shown that this occurs at a generator power of ~20 W.

Using the method of counter-propagating waves [4], we can obtain an expression for the amplitude of the microwave voltage across the *p–i–n* diodes in the energy-storing mode:

$$U_d = (4\lambda n/(cT_p(1+k_1)))\sqrt{\pi z_0 b k_1 Q_1 P \gamma^3/a}, \qquad (4)$$

where $n$ is the factor characterizing the excess of the microwave voltage across the *p–i–n* diodes over the voltage at the center of a uniform waveguide.

Assuming that $U_d$ is equal to the bias voltage $U_s$ and using (3) and (4), we obtain the maximum magnetic induction limited by the losses in the *p–i–n* diodes:

$$B_m = (2T_p U_s/(\pi\lambda n b \gamma^3))\sqrt{n}. \qquad (5)$$

The cavity coupling coefficient selected for this device is such that $T_p = 55$ ns, the measured value of $\eta$ is 0.6, the calculated excess factor is $n = 1.4$, and $U_s = 50$ V. Then, $B_m = 0.32$ mT.

Figure 2 shows a circuit diagram of the control unit for the *p–i–n* diodes. The latter are rapidly enabled by applying forward-current pulses to them. These pulses result from the amplification of trigger rectangular pulses from a Г5-60 generator. Two output amplification stages are connected in parallel in order to enhance the output current and to accelerate the charge-accumulation process in the *p–i–n* diodes. These stages are built using KT-914A transistors according to a cascode circuit. To rapidly switch the *p–i–n* diodes to the OFF state (to disperse the accumulated charge), in addition to a blocking dc voltage, pulses from a generator with a fast discharge of a capacitor through a КУ-112 thyristor are applied to the diodes. These pulses have an exponentially decaying trailing edge with a 30-V initial amplitude and a decay time constant of 0.6 μs. This circuit ensures the operation of the device at a pulse repetition rate of up to 40 kHz.

The microwave power is fed to the storage cavity from the output of a special generator [5] that yields output microwave pulses with a controlled duration, amplitude, and repetition rate. At a microwave-pulse duration and repetition rate of 1 μs and 40 kHz, respectively, the generator output-pulse power reaches 150 W.

According to (2), the microwave-pulse duration in the working cavity is determined mainly by the coupling coefficient $k$. The nominal duration (55 ns) is achieved upon the application of 40-ns-long trigger pulses to the control unit. It was established experimentally that the pulse duration in the working cavity could be reduced to 30 ns by shortening the trigger pulse to 10 ns. In this case, the energy does not return from the working to the storage cavity but rapidly dissipates in the *p–i–n* diodes. Figure 3 shows experimentally recorded shapes of microwave pulses in the working cavity at trigger-pulse durations of 40 and 10 ns.

Hence, using the effect of fast energy transfer in a pair of coupled cavities makes it possible to form in a high $Q$ cavity short microwave pulses with a duration much shorter than the time in which steady oscillations are established in them.

## ACKNOWLEDGMENTS

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