Optoelectronic Pulse Compression of Microwave Signals

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Abstract —**Optically switched transmission line resonators are shown to generate short microwave pulses of higher output peak power than the CW input signal. This kind of pulse compression is achieved by using the resonator as a storage element and an optoelectronic switch as the output mirror. A theoretical analysis of the efficiency of this device is presented. Experimentally, a peak power enhancement of 14 has been observed at a frequency of 1 GHz. A comparison with numerical results is finally carried out.**

I. Introduction

IN RECENT YEARS a growing interest has been dedicated to the possibility of optical generation of microwave signals by using the ultrafast switching properties of present optoelectronic switches [1]. Two ways can be distinguished depending on the kind of input used. First, a direct dc-to-RF conversion can be accomplished to generate microwave or millimeter-wave energy of high output power [2]–[5]. Second, the optoelectronic switch can be used to modulate a CW input signal and thus to achieve short microwave bursts [6], [7]. In both cases, the output waveform depends on the time response of the optical pulse and the optoelectronic switch and additionally on the influence of some pulse-forming networks [8].

Recently we proposed an optoelectronically switched resonator (OESR) to generate short microwave bursts of higher peak output power than the CW input [9]. This kind of optically performed microwave pulse compression can be achieved by using the microwave resonator as a storage element and the optoelectronic switch (OES) as an output mirror. Preliminary experiments have demonstrated this kind of power enhancement. In this paper we present a detailed theoretical description of pulse compression facilities of the OESR. We discuss also experimental results on an optimized device, which demonstrates that power enhancement factors of more than 14 are easily achieved with an OESR of high quality factor. Finally, the measurements are compared with numerical predictions.

II. Theory

In Fig. 1(a) the arrangement of the optoelectronically switched resonator is schematically displayed. The input capacitance and the optoelectronic switch, represented by its equivalent circuit of capacitance C_s shunted by the time dependent conductance $G(t)$, form the input and output mirrors of the transmission line resonator, respectively. The transmission line of length l is characterized by the phase velocity v and the attenuation constant α at the selected frequency of a CW input signal.

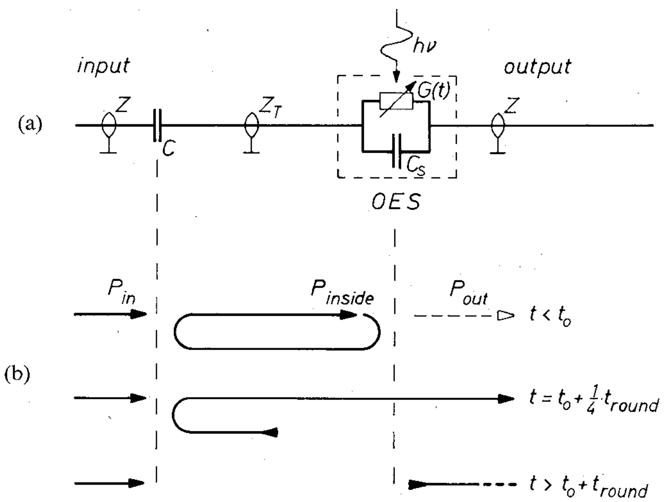

Fig. 1. The optoelectronically switched resonator (OESR). Sketch of (a) the device and (b) the traveling waves before and after illumination at time t_0.

A. Stationary Dark Case

First, we discuss the stationary dark case, where the OES only acts as a capacitor, since $G \cong 0$. Then the behavior of the whole device is that of a common transmission line resonator, as sketched in Fig. 1(b) at time $t < t_0$, where t_0 indicates the onset of illumination. For the following theoretical treatment, the power reflectivities R and R_c of the input and output mirror, respectively, are calculated to be

$$R = \left((\omega C)^{-2} + (Z - Z_T)^2\right) / \left((\omega C)^{-2} + (Z + Z_T)^2\right) \quad (1)$$

and

$$R_c = \left((\omega C_s)^{-2} + (Z - Z_T)^2\right) / \left((\omega C_s)^{-2} + (Z + Z_T)^2\right) \quad (2)$$

where Z denotes the characteristic impedance of the input and output port, and Z_T that of the resonator transmission line (see Fig. 1(a)); ω is the angular frequency of the input

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signal. It should be noted that in this case the reflectivities are independent of the direction of power flow.

The power transmittances of the input and output mirrors are then $(1-R)$ and $(1-R_c)$, respectively. Now the well-known Airy formula [10] describes the transmitted power of such a transmission line resonator, which, after division by the output transmittance $(1-R_c)$, yields the power P_{inside} of the traveling wave inside the resonator:

$$P_{\text{inside}} = P_{\text{in}} \frac{(1-R)T}{\left(1-\sqrt{R_c R}\,T\right)^2} \quad (3)$$

where resonance has been assumed. The power transmission factor of the transmission line of length l is

$$T = e^{-2\alpha l}. \quad (4)$$

With respect to the reflectivity R, the ratio in (3) is at maximum if

$$R = R_c T^2 \quad (5)$$

to give

$$\frac{P_{\text{inside}}}{P_{\text{in}}} = \frac{T}{1-R_c T^2}. \quad (6)$$

Equation (6) describes the effect of resonance step-up, leading to $P_{\text{inside}} \gg P_{\text{in}}$ if $T \cong 1$ and $R_c \cong 1$. In other words, in the stationary dark case the resonator is charged up by the traveling wave where the stored power depends on the number of reflected waves inside the resonator which contribute to the amplitude of the standing wave. Consequently, the output power in the stationary case is now

$$P_{\text{out}} = P_{\text{in}} \frac{T(1-R_c)}{1-R_c T^2} \quad (7)$$

which is always smaller than P_{in}.

B. Temporal Behavior

In the second step, we now discuss the temporal behavior of the output power of a charged OESR when the OES is illuminated (see Fig. 1(b) at $t > t_0$). For practical purposes, in the following a quasi-periodic wave is assumed throughout where the signal power is determined by the square of the amplitude. As a consequence, P_{inside} and P_{out} become time dependent and (3), (6), and (7) determine the values at $t \leqslant t_0$ only. Furthermore, the temporal dependence of the conductance G on the illuminating light pulse, which is basically described by processes such as carrier generation, drift, and recombination [2], is merely represented by a function $G(t)$. The capacitance of the OES is assumed to be sufficiently small so that the conductance $G(t)$ determines the reflectivity at times $t > t_0$ and the capacitance of the OES can be neglected. In this case, (2) cannot be applied and the time-dependent power reflectivity $R_s(t)$ for wave propagation inside the resonator at $t > t_0$ can now be obtained from

$$R_s(t) = \left(G^{-1}(t) - Z_T + Z\right)^2 / \left(G^{-1}(t) + Z_T + Z\right)^2. \quad (8)$$

The total power, which is dissipated in the OES and in the load resistance, is obviously $P_{\text{inside}}(t)\cdot(1-R_s(t))$, where $P_{\text{inside}}(t)$ is the time-dependent power of the traveling wave inside the resonator incident on the output mirror. Now the fraction of this power which is transmitted to the load resistance Z can be obtained from

$$P_{\text{out}}(t) = P_{\text{inside}}(t)\cdot \frac{Z}{\left(G^{-1}(t)+Z\right)}\cdot(1-R_s(t)) \quad (9)$$

leading to

$$P_{\text{out}}(t) = P_{\text{inside}}(t) \frac{4 Z_T Z}{\left(G^{-1}(t)+Z_T+Z\right)^2}. \quad (10)$$

As can be seen, $P_{\text{out}}(t)$ is determined by the temporal behavior of both the inside traveling wave and the conductance of the optoelectronic switch. Basically, $P_{\text{inside}}(t)$ is a decreasing function of time due to the discharge process, whereas $G(t)$ increases at first, reaches a maximum value $G_{\max}$, and decreases again. In particular, during the first round-trip time t_{round}, which is

$$t_{\text{round}} = 2l/v \quad (11)$$

the power $P_{\text{inside}}(t)$ is equal to the value of the stationary (dark) case. Therefore, for $t_0 < t < t_0 + t_{\text{round}}$, the output power can be estimated by combining (6) and (10), yielding

$$\frac{P_{\text{out}}(t)}{P_{\text{in}}} = \frac{4 Z_T Z}{\left(G^{-1}(t)+Z_T+Z\right)^2} \frac{T}{1-R_c T^2}. \quad (12)$$

As discussed above, the second factor in (12) can exceed unity by far. The first factor is determined by the time dependence of $G(t)$ of the OES and is always less than unity. It should be noted at this point, however, that the rise time of the conductance of an OES can be in the picosecond range and the maximum value of $G(t)$ of the order of Z^{-1} and Z_T^{-1}, so that the first factor in (12) can reach the order of unity within a fraction of a round-trip time. In that case the peak output power $\hat{P}_{\text{out}}$ as given by (12) for $G(t) = G_{\max}$ may be considerably larger than the power of the CW input signal.

For times larger than the round-trip time, $t > t_0 + t_{\text{round}}$, the following iterative procedure can be applied to get some additional analytical results. For that purpose, we compare the power of the traveling wave inside the resonator at two different times, separated by t_{round}. During that time interval, the traveling wave is twice reflected, at the input mirror and at the OES, and has sufferred two times from the attenuation factor T of the transmission line. Neglecting now the charging process, we obtain

$$P_{\text{inside}}(t + t_{\text{round}}) = P_{\text{inside}}(t)\cdot R \cdot R_s(t)\cdot T^2. \quad (13)$$

By means of (13), $P_{\text{inside}}(t)$ can be estimated iteratively. It is obvious that $P_{\text{inside}}(t)$ decreases with time since $R < 1$ and $R_s < 1$. By applying (10), $P_{\text{out}}(t)$ is the product of $P_{\text{inside}}(t)$ and the transmittance of the OES, and one also gets a decrease of $P_{\text{out}}(t)$ with time if again a picosecond rise time OES is used.

C. Special Cases

Moreover, in a first special and practical case of a steplike behavior of $G(t)$, i.e.,

$$G(t)=\begin{cases}0 & \text{if } t\leqslant t_0\\ G_{\text{on}} & \text{if } t>t_0\end{cases} \tag{14}$$

the time dependence of $P_{\text{out}}(t)$ can be expressed in an analytic way. At a given time $t=t'+nt_{\text{round}}$, where t' is a time during the first round-trip time with

$$t_0\leqslant t'\leqslant t_0+t_{\text{round}} \tag{15}$$

the output power is given by

$$P_{\text{out}}(t'+nt_{\text{round}})=P_{\text{out}}(t')\left(R\cdot R_s\cdot T^2\right)^n, \qquad n=1,2,3\cdots \tag{16}$$

where $P_{\text{out}}(t')$ is the output power during the first round-trip time, as discussed above. The reflectivity R_s is given by (8) with $G(t)=G_{\text{on}}$.

In a second special case of interest, we assume in addition to the steplike behavior of $G(t)$

$$G_{\text{on}}\gg Z_T^{-1} \tag{17}$$

and

$$Z_T=Z. \tag{18}$$

In this case, $R_s(t)$ vanishes for $t>t_0$ according to (8) and (14). As a result, one obtains

$$P_{\text{out}}(t)=\begin{cases}P_{\text{inside}}(t_0) & \text{if } t_0<t<t_0+t_{\text{round}}\\ 0 & \text{if } t\geqslant t_0+t_{\text{round}}.\end{cases} \tag{19}$$

Therefore, in this special, most interesting, and optimum case, a microwave burst is generated whose duration is that of the round-trip time, the amplitude being equal to the amplitude of the traveling wave inside the resonator in the stationary dark case. An optimization can be carried out as described above, where the "figure of merit" $T/(1-R_cT^2)$ of (12) plays an important role.

After any discharge process, the OESR is charged again by the input signal, and the output amplitude increases. The characteristic cycle time for that process is also calculated from the Airy formalism to be

$$\tau=t_{\text{round}}/\left(1-R_cT^2\right). \tag{20}$$

After this time, the difference of the output amplitude from the maximum stationary value is only $1/e$ of this value.

III. Experiment

The experimental arrangement of the OESR is sketched in Fig. 2. In contrast to our preliminary experiments in [9], we used 0.141-in semirigid coaxial cables as transmission lines. The dielectric material of the line has been removed over a length of $l=15$ cm, forming a low-loss coaxial air line. A variable gap in the inner conductor forms the input capacitance. In all experiments this capacitance has been tuned according to (5), yielding maximum output power. The OES, sketched in the inset of Fig. 2, is mounted by means of silver–epoxy between the inner conductors. The OES is an InP:Fe device with ohmic Au:Ge contacts, forming a gap of $s=12$ μm width, where the light of the laser diode is focused.

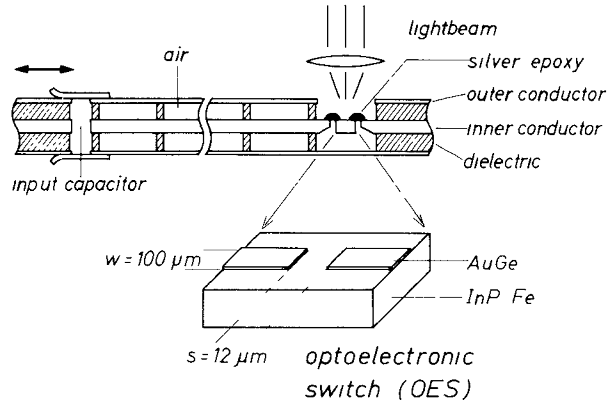

Fig. 2. Experimental arrangement of the OESR. In the inset a sketch of the optoelectronic switch is shown.

TABLE I
EXPERIMENTAL DATA OF THE DEVICE AT DIFFERENT FREQUENCIES

frequency (GHz)	R_c	T
1	0.9994	0.993
2	0.9976	0.989
3	0.9942	0.987
4	0.9886	0.983

Experimental data on the OESR without illumination were obtained by network analysis and are summarized in Table I. As can be seen, resonators with high quality factor are realized. The laser diode used in the experiments has a peak power of 1 W and a pulse width of 290 ps (FWHM) at a wavelength of 817 nm.

The dark resistance of the OES is of the order of 10^{10} Ω. In order to characterize the OES when illuminated, usual time-resolved photoconductance measurements have been carried out. For that purpose, a dc voltage has been applied and the OES has been illuminated by light pulses from the laser diode, described above. From the experimental data $Z=50$ Ω, $Z_T=60$ Ω, and $G_{\max}=0.011$ Ω^{-1}, the transmittance according to (10) has a peak value of 0.3 and the temporal FWHM is 1.3 ns due to carrier lifetime. The results have also been verified by microwave-switching experiments up to 4 GHz.

The apparatus used in the discharge experiments to be described in the following consists of a microwave generator, a pulse laser diode with power supply and pulse generator, and a sampling oscilloscope (rise time 28 ps) to observe the output voltage. The repetition rate of the laser diode is 10 kHz. In order to use the sampling oscilloscope,

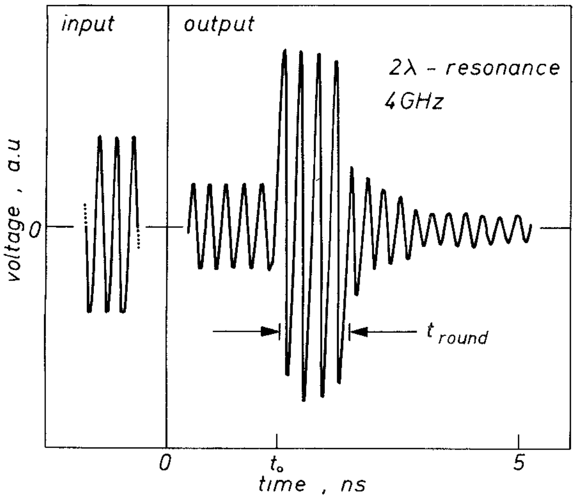

Fig. 3. Input and output voltage of the OESR at 4 GHz. Input power is in the range of 3 μW. For details, see text.

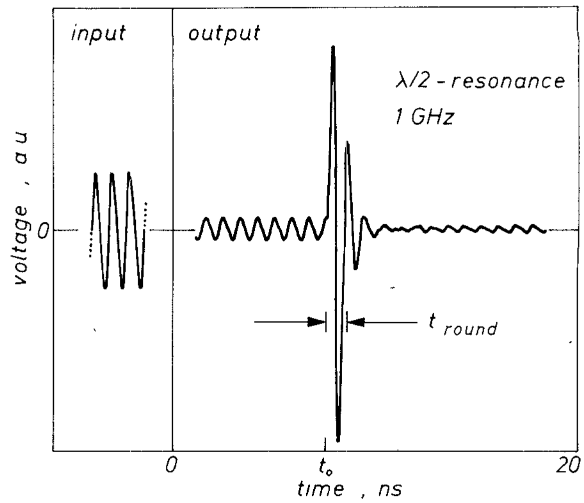

Fig. 4. Temporal behavior of input and output voltage of the OESR at 1 GHz. Input power is in the range of 30 μW. For details, see text.

which is triggered simultaneously with the laser diode, the low-frequency trigger signal and the microwave signal have to be phase locked. We have developed a microwave synthesizer system to achieve this phase locking. The overall time jitter between the 10-kHz signal and the 4-GHz signal was determined to be less than 80 ps.

In the following, experimental output waveforms of the OESR are presented. Fig. 3 displays the output voltage of the OESR driven at its 2 λ resonance of 4 GHz. Before illumination ($t < t_0$) the output voltage is smaller than the input voltage, which is displayed in the left part. After illumination, the output voltage increases steeply to a high value. At times $t > t_0 + t_{\text{round}}$, with $t_{\text{round}} = 1$ ns, the output voltage decreases sharply again, indicating that a large amount of the stored microwave power has left the resonator. After that decrease, the output signal does not vanish, indicating that the OESR has not completely been discharged. Fig. 4 displays a situation obtained at the fundamental $\lambda/2$ resonance at 1 GHz. Here the output waveform is nearly a monocycle of 1 GHz.

Discharge experiments have also been performed at microwave frequencies of 2 and 3 GHz. The temporal behavior of the envelope is similar to that of Fig. 3. In all experiments bursts of duration equal to the round-trip time and of high power are generated, due to the fact that the transmittance of the OES in the ON state is relatively high. On the other hand, the fact that the transmittance of the OES only reaches 0.3 explains that the resonator is not completely discharged during the first round-trip time. Since $G(t)$ is not constant, the amplitude decreases slightly during the second round-trip time and (16) cannot be applied.

In order to compare the experimental data quantitatively with the theory, the peak power enhancement factor $\hat{P}_{\text{out}}/P_{\text{in}}$ is calculated by means of (12), where the data of Table I and of the time-resolved photoconductance measurements of the OES have been used. The experimental values of peak power enhancement are obtained from the measurements at four different frequencies, as mentioned

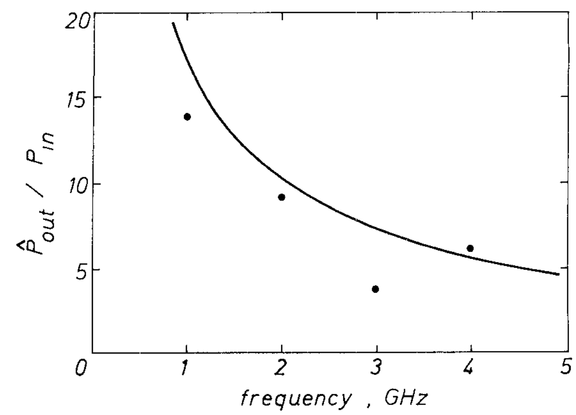

Fig. 5. Peak power enhancement factor versus frequency. Experimental data (·) and theory (solid line).

above. The results are shown in Fig. 5. As can be seen, the theoretical and the experimental data reveal quite good agreement. The deviations between experiment and theory are probably due to experimental tuning problems when the light is focused into the gap and when the input capacitance is varied according to (5) so that the device is not driven under optimum conditions. The measured value of the peak power enhancement factor itself has small errors, because P_{in} and $\hat{P}_{\text{out}}$ are measured with the same sampling oscilloscope. The highest power enhancement factor is observed at 1 GHz, where a value of $\hat{P}_{\text{out}}/P_{\text{in}} = 14$ has been obtained. With increasing frequency, the power enhancement decreases. This fact can be traced back to a decreasing T and R_c (see Table I) with frequency. A shorter resonator would lead to higher output powers at higher frequencies and to shorter pulses.

IV. Summary and Conclusions

In the present paper we have demonstrated both theoretically and experimentally that optoelectronically switched resonators can be used to generate very short bursts from a CW microwave source. Under optimum conditions the pulse duration is mainly determined by the resonator round-trip time and the peak power is very high compared with the available power from the generator. On the other hand, the maximum value of the peak output power will be determined by the breakdown threshold of the OES and the available optical pulse energy. We believe, however, that the efficiency of this type of pulse compression can even be increased by improved materials and technologies.

Finally, it should be noted that an integrated version of the device seems to be feasible, for example, where a Gunn diode, the resonator, and the OES are realized in MMIC technology. Additionally, the laser diode could also be integrated, leading ultimately to an integrated optoelectronic circuit of small size, high reliability, reproducibility, and potentially low costs for radar applications in different areas. It can be foreseen that the transmission line resonator can be realized in the form of a Schottky coplanar waveguide [11], [12], so that the resonance frequency can again be controlled electronically or even optically.

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