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PULSE-MODE SIMULATIONS OF RTD-LD CIRCUITS FOR VISIBLE LIGHT COMMUNICATION

V. B. YURCHENKO, L. V. YURCHENKO, M. CIYDEM

We suggest a new kind of circuit made of a resonant tunneling diode (RTD) and a laser diode (LD) for visible light communication. The circuit has a radio frequency (RF) resonant antenna joined to the RTD-LD unit with a microstrip section. The circuit can convert modulation pulses with no carrier into the pulses with an RF carrier. The RF pulses are radiated by the antenna for duplicating optical pulses emitted by the LD. The optical pulses also acquire the RF modulation that helps in detection of pulses by the RF filtering of optical signals.

Keywords: resonant tunneling diode, laser diode, visible light communication.

INTRODUCTION

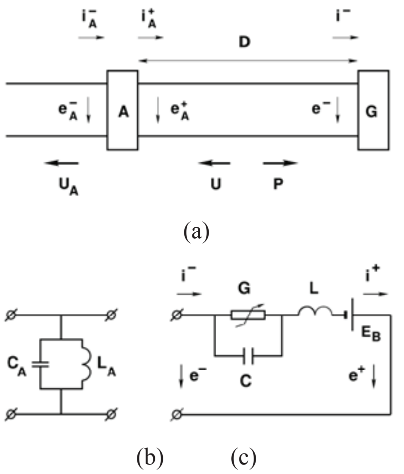
A visible light communication (VLC) technology is an attractive solution for providing broadband mobile communication services to the end-users with high speed of information delivery [1-5]. It has appealing advantages such as a possibility of using available lighting equipment based on the light emitting diodes (LEDs), though it has inherent limitations. The main limitations are the limited bandwidth of conventional LEDs (on the physical layer, the modulation frequency f is limited by 100 MHz), the difficulty of high-speed modulation of high-power LEDs, and the need of re-arrangement of lighting infrastructure. Further difficulties may appear if much chipper but much slower organic LEDs (OLEDs) would come to replace conventional LEDs.

A promising development in this area is the use of laser diode (LD) light sources. The LDs can provide a data bandwidth more than 100 times greater than the LEDs bandwidth [6]. The data rates in the excess of 100 Gb/s would be accessible with LD VLC systems at standard indoor illumination levels [7]. The LDs have higher current density and output power per unit area than LEDs, and multicolor LD lighting is shown to have no health concern on the human eye [8]. The LDs light is coherent and collimated, which is an advantage for point-to-point data transmission. In total, LD-based white VLC and lighting systems have a potential to outperform the ones based on LEDs. Multi-Gigabit data rates have been achieved in VLC systems based on the III-nitride LDs (e.g., 17.6 Gb/s in [6]). Eventually, the fabrication of LD arrays similar to LED arrays should be developed for these applications.

1. PROBLEM FORMULATION

An interesting version of an LD circuit was proposed in [9, 10]. The authors considered a system with an LD being driven by the resonant tunneling diode (RTD). This makes the circuit capable of operating at the frequencies up to 2 GHz [9]. The LD was an optical communication laser operating at around 1550 nm IR radiation wavelength with an average output power of 5 mW. The RTD-LD hybrid circuit was produced with a minimal length of bonding wires b accessible with manual manufacture ($b \sim 1$ mm) in order to minimize the inductance L of the system. Using the RTDs of small capacitance C, the authors observed self-oscillations at the frequencies of 350 – 400 MHz, 550 – 590 MHz, and 1.82 – 2.17 GHz, depending on the bonding wire length b and other parameters [9]. The authors also simulated the system dynamics while considering the structure as a lumped circuit [9, 10].

The aim of this work is to propose and analyze a more general kind of RTD-LD oscillator. In distinction from [9, 10], we consider a distributed system (Fig. 1) that, along with an RTD-LD unit (block G), contains a resonator antenna unit (block A), which is connected to the RTD-LD block by a section of microstrip line of length D and, at the same time, can radiate the electromagnetic waves U_A into an open section of microstrip line of an infinite length. The presence of microstrip section of length D creates the time-delay feedback in the system. The duration of time-delay is $T_D = 2D/c$, where c is the wave propagation speed in the microstrip section (for simplicity, we assume c is the speed of light in the



(a)

(b) (c)

Fig. 1. (a) – A microstrip circuit with (b) a resonator antenna A and (c) a generator section G based on the RTD-LD unit (notations show the current and voltage values, the circuit elements, and the waves propagating in the system)

free space). The time-delay feedback can produce complicated dynamics of oscillations such as the emergence of self-pulsing of high-frequency oscillations [11], nonlinear power combining [12], dynamical chaos [13], ultra-short pulse generation [14], etc.

The RTD-LD circuit is shown in Fig. 1 (c) as an element G of a G-block, which is specified by the current-voltage characteristics $I_G = I_G(V_G)$ (the I-V curve) with a region of negative differential resistance (NDR) as defined in [9, 10]. Self-oscillations could appear in such a system when the RTD-LD voltage V_G falls into the NDR region. In relative units, the I-V curve of RTD-LD circuit is presented as $i_G(e_G) = I_G / I_0 = G_0 F(e_G) / I_0$ where G_0 is the peak current coefficient, $e_G = V_G / V_0$, $V_0 = 1$ V, $I_0 = V_0 / Z_0 = 0.02$ A, $Z_0 = 50$ Ohm is the microstrip impedance, and $F(e_G)$ is the function defining the shape of I-V curve as specified in [10] in ampere units, with peak current $I_{G0} = 0.04$ A (then, $G_0 = 1$ and the peak value of i_G is $i_G = 2$). Equations describing the radio-frequency (RF) part of the system are presented in [11].

The LD optical output is modeled as explained in [10]. The rate equations for the electron and photon densities contain, among other terms, the excitation term proportional to the RTD-LD current I_G and two relaxation terms defined by the electron and photon lifetimes $\tau_n = 0.8$ ns and $\tau_p = 1.2$ ps, respectively. It is the value of $\tau_n \sim 1$ ns that makes the LD frequency-limited at $f \sim 1$ GHz. For the LD operating at $f \sim 100$ GHz [7], we expect $\tau_n \sim 10$ ps and consider this value in our simulations, while assuming the other LD parameters to be the same as in [10].

We start with the RF circuit parameters specified in [10], including the RTD capacitance $C = 5.5$ pF and the circuit inductance $L = 8$ nH, that makes the G-block intrinsic frequency $f_G = 0.76$ GHz (the actual self-oscillation frequency appears to be smaller). We also, typically, assume the resonator parameters $C_A = C$ and $L_A = L$ that makes the A-block intrinsic frequency f_A the same as f_G, though, occasionally, we consider the values $f_A = 0.76 - 76$ GHz.

Both the LD and RTD devices in [10] are specified by the same frequency limit of $f \sim 1$ GHz, though much faster LDs [7] and RTDs [15, 16] are available at present. Specifically, the RTDs can operate at the frequencies up to $f \sim 1$ THz, while having the quantum well-collector capacitance $C_{WC} \sim 1$ fF at nearly the same RTD current [16]. Assuming the inductance L is also reduced by, at least, 10 times, we can expect the G-block intrinsic frequency to approach $f_G \sim 100$ GHz that we also consider in simulations.

Notice, the time-delay circuit with a piece of transmission line between the G and A blocks can be treated as a model of real THz RTD structure integrated with a resonator antenna [16]. In this structure, the dominating capacitance and inductance values are C of RTD and L_A of resonator. In [16], the size of the RTD-resonator structure is small as compared to the radiation wavelength λ, though the structure is further integrated with planar Vivaldi antenna whose size is comparable with λ for the better radiation of waves into the free space. This extended component could also affect the operation of the oscillator. So, the analysis of the model systems considered in our research could be useful for a better understanding of the RTD-based THz oscillator structures presented in [16].

2. SIMULATION RESULTS

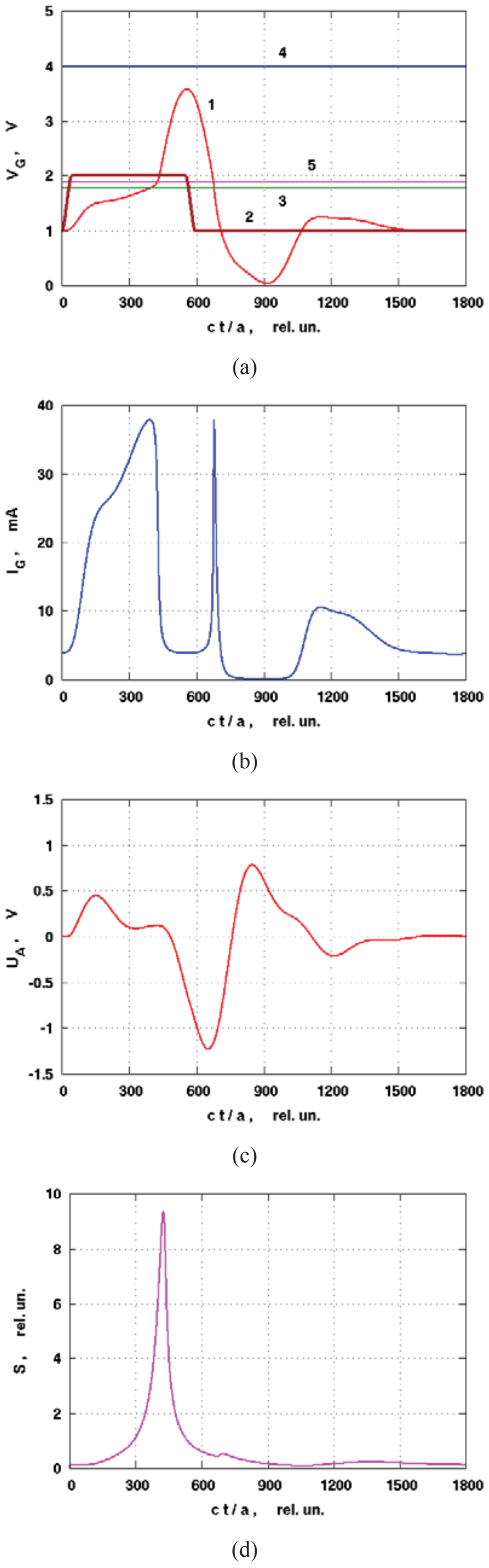
An RTD-LD circuit joint with a resonator antenna by a piece of transmission line can produce synchronous generation of both the RF pulse radiation and the RF-modulated optical pulses. This feature could be of interest for the development of new kinds of optical communication systems. We start our simulations by using a set of parameters provided in [10] and assuming the length of microstrip section $D = 10$ mm (in relative units $d = D / a = 10$ where $a = 1$ mm) and the length of the excitation pulse $T_p \sim 2$ ns ($cT_p / a = 600$).

Fig. 2 shows the results that demonstrate a possibility of a single, well-shaped LD optical pulse excitation while the RF radiation pulse U_A is not well formed (the light intensity normalization unit is the same for all the plots presented below).

The microstip circuit at these parameters is not yet fast enough for pulses of $T_p = 2$ ns (the relevant frequency is $f_p = 1 / T_p = 0.5$ GHz, while the pulse repetition frequency is $f_{REP} = 0.25$ GHz at 50% duty cycle). The results are similar at smaller values of microstrip length D, except for lower peak intensity (e.g., $S = 7$ at $D < 1$ mm). The increase of D to $D = 40$ mm increases the light peak to nearly maximum $S = 16$ at the same pulse width, though further increase of D reduces the peak and begins to deform the light pulse and increase its duration.

Now, we consider the circuit that has 10 times faster RTD and resonator response ($f_G = f_A = 7.6$ GHz when the other parameters are the same as above, except for the microstrip length being $D = 5$ mm). The simulation results are shown in Fig. 3.

The simulations reveal the effect of RF modulation of light intensity of the optical pulse along with gradual increase of the light power during the process of light emission. The RF modulation of light intensity S is induced by the RF oscillations of RTD-LD current that also creates the oscillations of radiated RF waveform U_A. The oscillations occur at the frequency $f_{RF} = 2.6$ GHz.



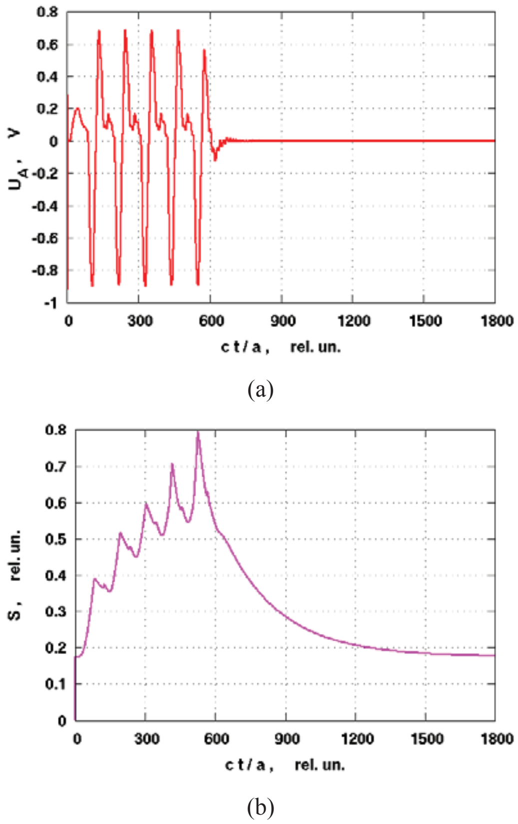
(a)

(b)

(c)

(d)

Fig. 2. The pulse of (a) RTD-LD voltage (curve 1), (b) RTD-LD current, (c) RF output, and (d) LD light pulse intensity S when $G_0 = 1$, $d = 10$, $f_G = f_A = 0.76$ GHz, and the excitation pulse length $T_p = 2$ ns (curve 2; lines 3 to 5 show the voltage values of lower and upper borders of NDR region and of the peak of negative differential conductance, respectively)



(a)

(b)

Fig. 3. The RTD-LD pulse of (a) RF output and (b) LD optical pulse at $G_0 = 1$, $d = 5$, $f_G = f_A = 7.6$ GHz, and $T_p = 2$ ns

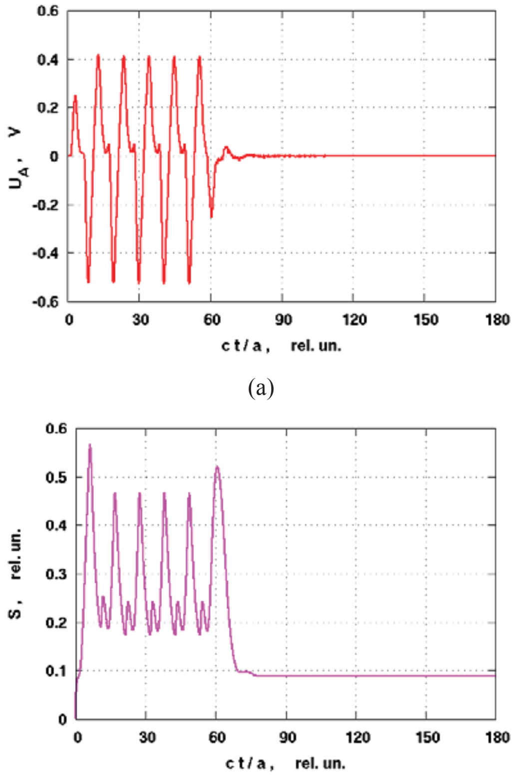
With decreasing the microstrip length to $D = 1$ mm and below, we observe a slight increase of the RF oscillation frequency up to $f_{RF} = 3.4$ GHz. On the contrary, with increasing D to $D = 20$ mm, we reduce f to $f_{RF} = 1.5$ GHz and slightly increase the light intensity (to $S = 1$), though further increase of D spoils the modulation shape and destroys the RF oscillations.

Finally, we analyze the main circuit of our interest, which is the case when the RTD and resonator frequencies are $f_G = f_A = 76$ GHz (Figures 4 – 6).

In this case, we reduce the LD electron lifetime parameter to $\tau_n \sim 10$ ps (see above) so that the LD optical output could follow more frequent RF oscillations of the RTD circuit. Also, we assume twice smaller RTD peak current ($G_0 = 0.5$), which is more typical for high-frequency devices [16], and choose $D = 1$ mm.

In this setting, we consider two options for obtaining high frequency oscillations. In the first case (case #1), we assume further proportional decrease of all values of capacitance and inductance as we did before.

In the second case (case #2), the RTD capacitance is made 100 times smaller as compared to the case in Fig. 3 (i.e., C and C_A are reduced to $C = C_A = 5.5$ fF) but the inductance is left the same ($L = L_A = 0.8$ nH) that makes, possibly, a more realistic system. In this case, at the greater pulse voltage $V_B = 3$ V, we can get a short burst of RF oscillations or a single RF peak even at the short pulse length $T_p = 50$ ps and $T_p = 25$ ps, respectively.



(a)

(b)

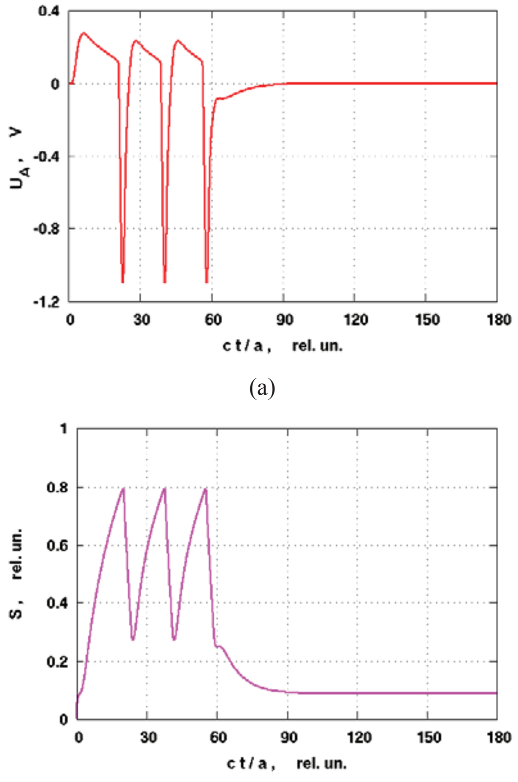
Fig. 4. Case #1 of excitation of (a) RF output and (b) LD optical pulse at $G_0 = 0.5$, $d = 1$, $f_G = f_A$=76 GHz, and $T_p = 0.2$ ns

Fig. 4 shows the results of simulations in case #1. Here we observe a well-defined pulse of RF oscillations and deep modulation of light intensity. The pulse length is now $T_p = 0.2$ ns, which is 10 times smaller as compared to Figs. 2 and 3, that corresponds to the pulse data rate of 2.5 Gb/s (at 50% duty cycle). The RF frequency in this case is $f_{RF} = 28.4$ GHz.

Fig. 5 shows the simulation results in case #2. In this case, the RF oscillation frequency is $f_{RF} = 16.7$ GHz. It is nearly twice less than the frequency obtained in case #1, though the pulses of both the RF and light signals are well formed and well modulated.

Fig. 6 shows a possibility of exciting a short burst of RF oscillations in the system of case #2 by increasing the pulse peak bias voltage to $V_B = 3$ V when reducing the pulse duration to $T_p = 50$ ps. With a shorter pulse, at least one RF peak can be excited at the pulse length $T_p = 25$ ps. These pulse durations correspond to the data rate of 10 and 20 Gb/s, respectively, assuming 50% duty cycle of periodic pulse sequence.

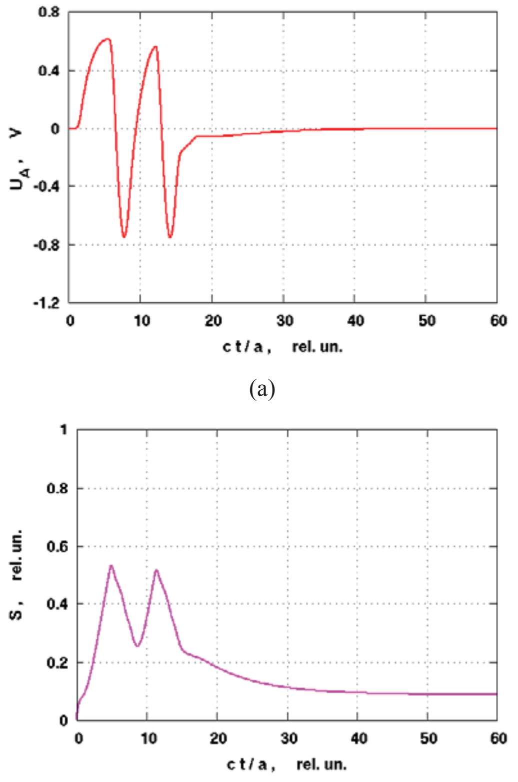
An essential issue in making high-speed VLC systems is the use of sufficiently fast photo-detectors. We believe the detector arrays will be used for this purpose, similarly to the LED, LD, RTD, and RTD-LD circuit arrays.



(a)

(b)

Fig. 5. Case #2 of excitation of (a) RF output and (b) LD optical pulse at $G_0 = 0.5$, $d = 1$, $f_G = f_A$=76 GHz, and $T_p = 0.2$ ns



(a)

(b)

Fig. 6. Case #2 of excitation of (a) RF output and (b) LD optical pulse when the external pulse bias voltage is $V_B = 3$ V and the pulse length is $T_p = 0.05$ ns ($cT_p / a = 15$)

For the direct detection of RF modulation of light pulses, an interesting device is the RF optical heterodyne 100 GHz photo-detector proposed in [17]. The device is specified by the RF response $S_{RF} = 2$ dBm, the RF bandwidth $f_{RF} = 100$ GHz, the sensitivity to 1550 nm IR radiation with photo-response 0.15 A/W, and the junction parameters of capacitance $C_{tot} = 36$ fF, inductance $L = 85$ pH, and series resistance $R_s = 15$ Ohm.

Development of a detection system capable of processing RF modulation of optical signals in free-space propagation channels is an important goal in the future light communication technology.

CONCLUSIONS

An RTD-LD circuit with a resonator antenna can be used for synchronous generation of both the RF pulse radiation and the RF modulated optical pulses. This possibility could be of interest for the development of new kinds of optical communication systems.

Our simulations of these circuits have shown a diversity of RF modulation effects and basic conditions for their implementation. A short piece of transmission line is helpful for the RF excitation and light modulation in response to the external pulse signal. It is similar to the stub effect in the excitation of a waveguide system. The optimal length of the piece depends on the phase shift of the feedback signal reflected from the antenna and has to be found from simulations of these circuits.

The period of oscillations of RTD-LD circuit has to be small as compared to the pulse duration of digital signal. In the opposite case, even if a sharp pulse is formed, an extra time is needed for damping the excitation between the pulses. This kind of relaxation delay is quite a common feature in laser systems.

In a high-speed RTD-LD system, the optical output of modern LDs is, generally, capable of following the RF oscillations of the RTD driver. In a slow RTD-LD system, even though narrow light peaks could appear with short excitation pulse, the RF oscillations may not be excited.

The arrays of RTD-LD circuits, which are made as the chip-on-board (COB) structures similar to the LED arrays, are expected to be a promising solution for the development of hybrid lighting and VLC applications. For the better operation of circuits, the RTD-LD frequency should essentially exceed the data transmission bandwidth as presented at the physical layer. This could allow one to implement the effect of RF modulation of optical pulses along with radiation of RF pulses for enhancing the detection of extremely weak data signals.

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Vladimir Yurchenko, M.Sc.(1980), Ph.D. (1984), D.Sc.(1994), occupied research and teaching positions at the NTU "KhPI" (1980-1995), A. Ya. Usikov Institute for Radiophysics and Electronics of the National Academy of Sciences of Ukraine (IRE NASU, 1995-2001 and 2008-2014, Kharkiv, Ukraine), Bilkent University (1996-1999, Turkey), National University of Ireland Maynooth (NUIM, 2000-2007, Ireland), Karatay University (2015, Turkey) and, on the TUBITAK-EU Fellowships, at the Engitek Engineering Technologies Ltd (2015-2017) and Gazi University (2014, 2018) in Ankara, Turkey. At the NUIM, he contributed to the design of the ESA PLANCK radio-telescope by developing ultra-fast PO-PO simulations of dual-reflector systems. His research interests are in the theory of semiconductors and electronic devices, hot-electron transport, plasma physics, electromagnetic wave generation, propagation, and scattering, antenna simulations, and mm-wave photonics.

Lidiya Yurchenko, M.Sc. (1980), Ph.D. (1991), Senior Research Scientist at the Dept. of Nonlinear Dynamics of Electronic Systems, A.Ya. Usikov Institute for Radiophysics and Electronics of the National Academy of Sciences of Ukraine (IRE NASU), Kharkiv, Ukraine. Research interests: computer simulations of the electromagnetic dynamical chaos in electronic systems, ultrabroad-band oscillations, generation of ultra-short pulses, and spatial power combining.

Mehmet Ciydem was born in Ankara, Turkey. He received his B.Sc., M.Sc. and Ph.D. degrees all in electrical engineering from Middle East Technical University (METU), Ankara, Turkey with high honours. After working in defence industry (Aselsan, Havelsan, TAI) for many years, he founded Engitek Ltd company where he is president. He is also one of the founders and board member of Communication Technologies Cluster (CTC) in Turkey. Dr. Ciydem is an Associate Professor of electromagnetics and communications. He lectures occasionally in several universities (Bilkent Univ., Gazi Univ., Karatay Univ., Hacettepe Univ., and Army War Academy). His research interests are in the areas of electromagnetics, antennas, RF/micro-wave engineering, radar, communication systems and mobile communications.

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Юрченко В. Б. **Импульсное моделирование РТД-ЛД цепей для видимой оптической связи** / В. Б. Юрченко, Л. В. Юрченко, М. Чийдем // Прикладная радиоэлектроника: науч.–техн. журнал. – 2018. – Том 17, № 1, 2. – С. 66 –71.

Предложено новый тип схемы, состоящей из резонансно-туннельного диода (РТД) и лазерного диода (ЛД) для видимой оптической связи. Схема имеет сверхвысокочастотную (СВЧ) резонансную антенну, соединенную с РТД-ЛД блоком микрополосковой секцией. Схема может преобразовывать импульсы модуляции без несущей в СВЧ импульсы. СВЧ импульсы излучаются антенной для дублирования оптических импульсов, излучаемых ЛД. Оптические импульсы также приобретают СВЧ модуляцию, которая помогает в обнаружении импульсов посредством СВЧ-фильтрации оптических сигналов.

Ключевые слова: резонансно-туннельный диод, лазерный диод, видимая оптическая связь.

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Юрченко В. Б. **Імпульсне моделювання РТД-ЛД схем для видимого оптичного зв'язку** / В. Б. Юрченко, Л. В. Юрченко, М. Чийдем // Прикладна радіоелектроніка: наук.–техн. журнал. – 2018. – Том 17, № 1, 2. – С. 66–71.

Запропоновано новий тип схеми з резонансно-тунельного діода (РТД) і лазерного діода (ЛД) для видимого оптичного зв'язку. Схема має надвисокочастотну (НВЧ) резонансну антену, з'єднану з РТД-ЛД блоком мікрополосковою секцією. Схема може перетворювати імпульси модуляції без несучої в НВЧ імпульси. НВЧ імпульси випромінюються антеною для дублювання оптичних імпульсів, випромінюваних ЛД. Оптичні імпульси також набувають НВЧ модуляцію, яка допомагає у виявленні імпульсів за допомогою НВЧ-фільтрації оптичних сигналів.

Ключові слова: резонансно-тунельний діод, лазерний діод, видимий оптичний зв'язок.

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