On the Theory of a Pulse Microwave-Pumped Laser

Valerii Semenets
Department of Metrology and Technical Expertise
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
E-mail: valerii_semenets@ieee.org

Mykhailo Kopot
Department of Software Engineering
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
E-mail: mykhailo.kopot@nure.ua

Alexander Gritsunov
Department of Microelectronics, Electronic Devices and Appliances
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
E-mail: gritsunov@gmail.com

Igor Bondarenko
Department of Microelectronics, Electronic Devices and Appliances
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
E-mail: igr.bond@gmail.com

Elman Yunusov
Department of Microelectronics, Electronic Devices and Appliances
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
E-mail: yunusov.elman@gmail.com

***Abstract*—A new construction of the microwave-pumped laser based on the light-pumping cell that uses radiation of sulfur vapor exposed to electromagnetic waves of the microwave band is described. Advantages of this design are the simple structure, high efficiency of the optical pumping cell, the possibility of cooling the pumping element, and easiness of modifying the emission spectrum of the optical pumping by changing the chemical composition of admixtures in the sulfur light-emitting cell. A mathematical tool for the simulation of the short-pulse operation of the microwave-pumped laser is proposed basing on the generalized wave equation solving for a regular transmission line with essentially nonlinear dispersion characteristic and substantial dissipation. Possible techniques for the numerical solving the generalized wave equation are discussed.**

***Keywords*—microwave-pumped laser, sulfur lamp, pulse operation, generalized wave equation, numerical simulation**

I. INTRODUCTION

The range of lasers usage is as wide as no one of other electron devices has. Many technological, scientific, medical, military, and entertaining laser applications have been proposed and realized since the invention of this device in 1958 [1]. The high coherency, monochromaticity, and ability to reach extra-large optical powers are the properties which enable it for those characteristic applications. Despite the impressive progress in the quantum electronics for recent decades, some new technical decisions appear regularly as well as modeling technique improves. In this paper, a prospective combination of an optical quantum generator with another recent invention, microwave-pumped power sulfur lamp [2, 3], is described and analyzed.

II. CONSTRUCTION OF THE MICROWAVE-PUMPED LASER WITH SULFUR LAMP PUMPING CELL

It is known that lasers generally use optical pumping. As an energy source, it may be used flashlamps, semiconductor emitters or sunlight [1]. Laser constructions with microwave-excited gas discharge (see, e.g., [4]) are also known, which consist of a power supply with a magnetron, waveguide and gaseous light-emitting element.

Disadvantages of those constructions are the complexity of mechanical adjustment and alignment together with the impossibility of calculating the fraction of magnetron's power required to maintenance of the discharge and laser pumping, due to the reflection of microwave radiation back to the magnetron from the discharge and from artificially imposed inhomogeneities. This leads also to the formation of standing waves, abnormality of the magnetron and reducing the effective radiated power.

The most near the structure by the combination of features is the design of solid-state laser with an external ignition, comprising a pump lamp, and optical resonator is an active element which is arranged parallel to the lamp pump [5]. The disadvantages of the known designs are the destruction of the coating as a result of significant heat pump lamp bulb, which limits the pulse repetition frequency, the inability to control the spectrum of the laser radiation, and low efficiency.

A new construction of the microwave-pumped laser based on the light-pumping cell that uses radiation of sulfur vapor exposed to electromagnetic waves of the microwave band was recently proposed. The sulfur lamp is a highly effective electrodeless visible-spectrum lighting system. Its light is generated by sulfur plasma that has been excited by power microwave radiation. This is one of the most modern modifications of the plasma lamps. The sulfur lamp technology was developed in the early 1990s [2] and it appeared to be very promising. Since 2005, lamps are being manufactured for commercial purposes.

The laser with the sulfur lamp cell, in addition to an active element, an optical resonator, and a pumping lamp itself, contains a waveguide, a microwave generator, a cooling device that is disposed on the outer surface, wherein the active element is disposed within the lamp. The pumping sulfur lamp is located inside a matched microwave waveguide or cavity resonator, which perform also the role of the optical reflector.

Advantages of this laser construction include the simple structure, high efficiency of the optical pumping cell, the possibility of cooling the pumping element, small reflection of the microwave radiation generator in the reverse direction. Also, it is easy to modify the emission spectrum of the optical pumping by changing the chemical composition of admixtures in the sulfur light-emitting cell, if necessary.

Fig. 1 shows a construction of the new microwave-pumping laser with a sulfur lamp cell, which contains an active element 1, a microwave resonator or waveguide composed of the inner gauze foil 2 and an outer metal tube 3, the outer surface of those has cooling fins 4 for the air cooling. The inner surface of the outer metal tube of the microwave

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resonator (or waveguide) has a mirror coating and acts as an optical reflector. Ends of this tube are closed with respective ends of the transparent grid foil 2 with metal flanges 5. There is a flask with sulfur vapor 6 inside the microwave resonator or waveguide. A pulse microwave pumping generator 8 is connected to the interaction cavity through the waveguide 7.

The system operates as follows. Microwave generator 8 is supplied with the control pulses. Further, the electromagnetic wave of the microwave generator 8 through the waveguide 7 flows into the interaction cavity. Under the influence of electromagnetic waves onto the sulfur vapor with admixtures in the flask 6, light emission occurs, which is reflected from the mirror internal surface of the outer metal tube 3 and through the gauze foil 2 reaches the laser active element 1. The laser light gets out from this active element. All the time of the device operation, it is possible to cool the sulfur lamp via the cooling fins 4 located on the external surface 3 of the microwave resonator or waveguide.

The proposed design, in addition to its manufacturing simplicity, improves the efficiency of the device as a whole and allows the use of different types of active element. The significant advantage of the above-described construction is the possibility of the radiation spectrum control by means of variation of the emitting media chemical composition.

The main problem appeared in all known microwave-pumped laser structures is to ensure the energy input to the sulfur plasma discharge uniform along the length of the discharge cell [5]. The emergence of this problem is due to the fact that in the microwave range the radiation wavelength becomes comparable (or even less) to the length of the discharge tube of the optical resonator (this is the difference between microwave and RF), which results in insufficiently proper coordination of the microwave generator and the discharge zone, which is the load this generator, to the formation of various kinds of reflections and standing waves. The appearance of standing waves leads to a substantially inhomogeneous energy input along the length of the discharge tube, which can lead to a breakdown of lasing.

Some issues appear for short-pulse microwave-pumped lasers, which may be especially effective if compression pulse formers [6, 7] are used for the pumping. The problems are caused by transient phenomena in light-emitting sulfur plasma discharge as well as in the active media of the quantum generator. The complex theoretical investigation of the non-stationary effects requires the quantum electrodynamics methods [8]. However, some specific issues can be studied with the classic electrodynamics' equations only.

III. MATHEMATICAL TOOL FOR SIMULATION OF THE PULSE-PUMPING SYSTEM

It is of importance for short-pulse laser systems to ensure consistent procedures of the microwave waveguide powering, the sulfur gas discharge ignition, and the quantum stimulation-deexcitation of the actuating medium. Only the first issue is considered in this paper. The microwave waveguide with the sulfur vapors may be interpreted as regular transmission line with essentially nonlinear dispersion characteristic and substantial dissipation. The known methodic of the calculation of nonstationary fields in such lines [9 – 12] can be used.

The continuous approximation of the regular dispersive line [10] is used here. In the Fourier approach, the electric field in the system $\vec{E}(t,x,y,z)$ can be calculated as a series in the longitudinal wavenumber β :

$$\vec{E}(t,x,y,z) = \mathrm{Re}\Big\{\vec{E}_g(x,y,z,\beta_b)U_g(t,z) + \\ +i\frac{\partial\vec{E}_g(x,y,z,\beta_b)}{\partial\beta}\cdot\frac{\partial U_g(t,z)}{\partial z}e^{-i\beta_b z}e^{i\omega_{rb}t}\Big\},$$

where $\vec{E}_g(x,y,z,\beta_b)$ is so-called regular mode of the line [complex envelope of the line eigenmode $\vec{E}_e(x,y,z,\beta)$ in the longitudinal direction *z*, so that $\vec{E}_e = \vec{E}_g\exp(-i\beta_b z)$]. $U_g(t,z)$ is a temporal and longitudinal dependence of the regular mode complex envelope. The subscript *b* implies that an item is taken at some base longitudinal wavenumber and frequency of respective normal mode ω_r . In the D'Alembert approach, the electric field is evaluated as a series

$$\vec{E}(t,x,y,z) = \mathrm{Re}\Big\{\vec{E}_g(x,y,z,\omega_b)U_g(t,z) - \\ -i\frac{\partial\vec{E}_g(x,y,z,\omega_b)}{\partial\omega}\cdot\frac{\partial U_g(t,z)}{\partial t}e^{-i\beta_{rb}z}e^{i\omega_b t}\Big\},$$

where the subscript *b* implies that an item is taken at some base frequency and longitudinal wavenumber of respective normal mode β_r .

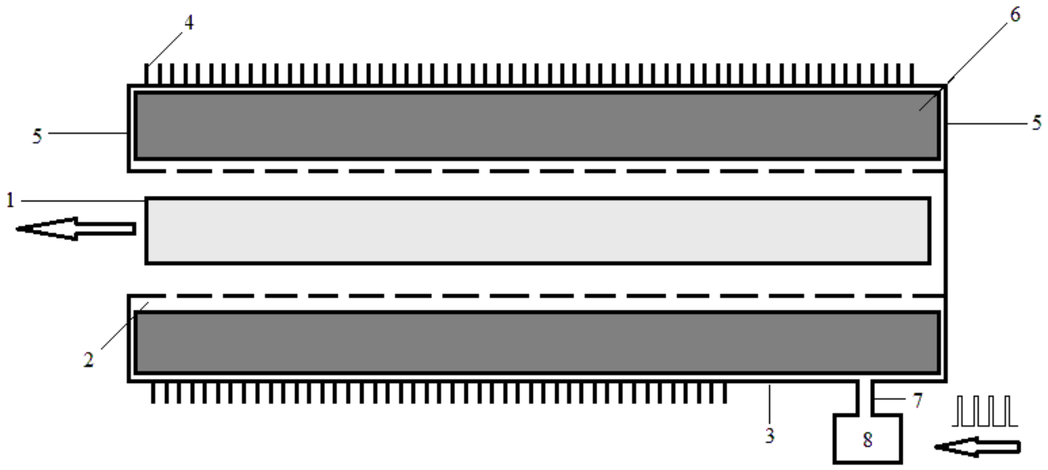

Fig. 1. Construction of the laser with a microwave pumping.

Generalized wave equations for U_g in the Fourier and the D'Alembert approaches respectively are

$$\begin{aligned}&\frac{\partial U_g}{\partial t}+\delta_{rb}U_g+i\frac{d\delta_{rb}}{d\beta}\frac{\partial U_g}{\partial z}+\frac{d\omega_{rb}}{d\beta}\frac{\partial U_g}{\partial z}+\frac{i}{2}\frac{d^2\omega_{rb}}{d\beta^2}\frac{\partial^2 U_g}{\partial z^2}=\\&=-\frac{1}{8W_{gb}}\int_{S_\perp}\vec{E}_g^*(x,y,z,\beta_b)\vec{J}(t,x,y,z)dS+\\&+\frac{i}{8W_{gb}^2}\frac{dW_{gb}}{d\beta}\frac{\partial}{\partial z}\int_{S_\perp}\vec{E}_g^*(\ldots)\vec{J}(\ldots)dS-\\&-\frac{i}{8W_{gb}}\frac{\partial}{\partial z}\int_{S_\perp}\frac{\partial\vec{E}_g^*(\ldots)}{\partial\beta}\vec{J}(\ldots)dS\end{aligned}\qquad(1)$$

and

$$\begin{aligned}&\frac{\partial U_g}{\partial z}+\alpha_{rb}U_g-i\frac{d\alpha_{rb}}{d\omega}\frac{\partial U_g}{\partial t}+\frac{d\beta_{rb}}{d\omega}\frac{\partial U_g}{\partial t}-\frac{i}{2}\frac{d^2\beta_{rb}}{d\omega^2}\frac{\partial^2 U_g}{\partial t^2}=\\&=-\mathrm{sgn}(v_{gr})\frac{Z_{rb}}{2U_1^2}\int_{S_\perp}\vec{E}_g^*(x,y,z,\omega_b)\vec{J}(t,x,y,z)dS+\\&+\mathrm{sgn}(v_{gr})\frac{i}{2U_1^2}\frac{dZ_{rb}}{d\omega}\frac{\partial}{\partial t}\int_{S_\perp}\vec{E}_g^*(\ldots)\vec{J}(\ldots)dS+\\&+\mathrm{sgn}(v_{gr})\frac{iZ_{rb}}{2U_1^2}\frac{\partial}{\partial t}\int_{S_\perp}\frac{\partial\vec{E}_g^*(\ldots)}{\partial\omega}\vec{J}(\ldots)dS,\end{aligned}\qquad(2)$$

where $\vec{J}(t,x,y,z)$ is the complex envelope of exciting current density $\vec{j}(t,x,y,z)$ at β_b and ω_b respectively; $\delta_r(\beta)$ and $\alpha_r(\omega)$ are damping factor and attenuation coefficient of the line eigenmode respectively; $S_\perp$ is the line transverse (x,y) section; $W_g(\beta)$ and $Z_r(\omega)$ are the linear unit energy and coupling impedance of the regular mode respectively; U_1 is the normalizing voltage; $v_{gr}=d\omega_r/d\beta$ is the group velocity.

After approximation of the line attenuation and dispersion characteristics within the chosen frequency band with $\delta_r(\beta)\approx a_0+a_1\beta+\ldots$, $\omega_r(\beta)\approx b_0+b_1\beta+b_2\beta^2+\ldots$ polynoms, for the Fourier approach, or with $\alpha_r(\omega)\approx a_0+a_1\omega+\ldots$, $\beta_r(\omega)\approx b_0+b_1\omega+b_2\omega^2+\ldots$ polynomials, for the D'Alembert approach, finite-difference equations are constructed. The orders of the polynomials and of the equations (1) and (2) in z or t directions respectively may be increased, if needs. The equations are solved with explicit or implicit finite-difference schemes. The right-hand parts of the wave equations may be substituted with some source function $s(t,z)$, which emulates entering the pulse into the line by an input signal.

IV. USED NUMERICAL TECHNIQUE

Consider methods of integrating the generalized wave equations (1) and (2). The underlying expression for both is non-uniform transport equation:

$$\frac{\partial U(t,z)}{\partial z}+\frac{1}{v_g}\frac{\partial U(t,z)}{\partial t}=f(t,z)\qquad(3)$$

modified with terms considering the nonlinearity of dispersion characteristics and wave attenuation. To solve (3) with a finite-difference method, an implicit or explicit pattern of the first-order approximation may be generally used. The explicit scheme is conditionally stable when $\Delta t\le\Delta z/|v_g|$, where Δt and Δz are the step sizes along the time and the longitudinal coordinate, respectively. The implicit scheme is absolutely stable.

However, the testing calculations for linear ("cold") regular electrodynamic system show that the first-order finite-difference approximation does not provide adequate accuracy of solutions of the generalized wave equations (1) and (2) for any more or less significant relative width of the signal bandwidth (of the order about 1 % or more of the base frequency). Therefore, the problem arises of choosing stable second-order difference schemes suitable for the integration of this equation.

The only possible template three-layer explicit second-order approximation scheme for the solving equation (2) is shown in Fig. 2 (a). The corresponding finite-difference approximation is written as:

$$\begin{aligned}&\frac{\partial U_k^l}{\partial z}\approx\frac{U_{k+1}^l-U_{k-1}^l}{2\Delta z};\\&\frac{\partial U_k^l}{\partial t}\approx\frac{U_k^{l+1}-U_k^{l-1}}{2\Delta t};\\&\frac{\partial^2 U_k^l}{\partial t^2}\approx\frac{U_k^{l-1}-2U_k^l+U_k^{l+1}}{\Delta t^2},\end{aligned}$$

where the index k corresponds to the coordinate z; index l to coordinate t.

This scheme is conditionally stable when $\Delta t\le\Delta z/|v_g|$. For equation (1), an explicit two-layer diagram of a second-order approximation is impossible to be construct.

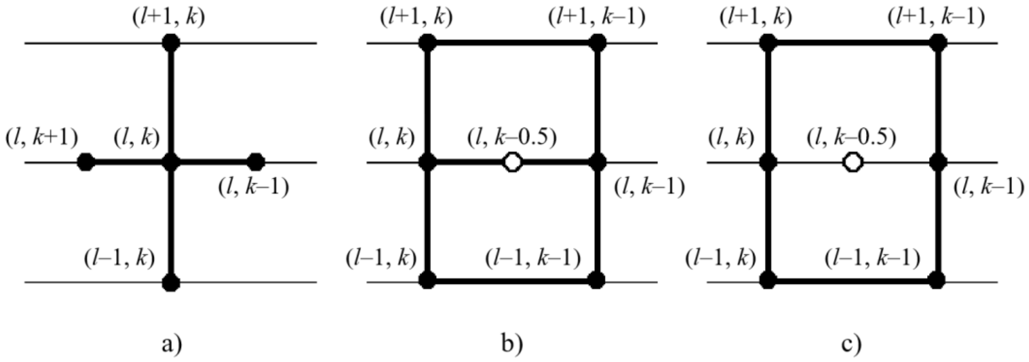

Fig. 2. Computational patterns for the three-layer scheme.

In addition to limiting the size of the time step, the disadvantage of this template is the need for extending the definition of the boundary conditions at the output end of the line. Extrapolation of amplitude with a power polynomial (up to the third order) does not provide convergence of solutions. Harmonic extrapolation at three points:

$$U_{k+1}^{l} = \frac{(U_k^l)^2 + U_{k-2}^l U_k^l - (U_{k-1}^l)^2}{U_{k-1}^l}$$

is suitable only for monochromatic U_g. Thus, second-order explicit scheme is unacceptable for the integration of (2).

Alternatively, we can suggest an implicit scheme of the same order of approximation with weights pattern which is shown in Fig. 2 (b). The corresponding finite-difference approximation has the form:

$$\begin{aligned}
&U_{k-0,5}^{l} \approx \sigma \frac{U_{k-1}^{l-1} + U_k^{l-1} + U_{k-1}^{l+1} + U_k^{l+1}}{4} + (1-\sigma)\frac{U_{k-1}^{l} + U_k^{l}}{2};\\
&\frac{\partial U_{k-0,5}^{l}}{\partial z} \approx \frac{\sigma}{2}\frac{U_k^{l-1} - U_{k-1}^{l-1}}{\Delta z} + (1-\sigma)\frac{U_k^{l} - U_{k-1}^{l}}{\Delta z} + \frac{\sigma}{2}\frac{U_k^{l+1} - U_{k-1}^{l+1}}{\Delta z};\\
&\frac{\partial U_{k-0,5}^{l}}{\partial t} \approx \frac{1}{2}\frac{U_{k-1}^{l+1} - U_{k-1}^{l-1}}{2\Delta t} + \frac{1}{2}\frac{U_k^{l+1} - U_k^{l-1}}{2\Delta t};\\
&\frac{\partial^2 U_{k-0,5}^{l}}{\partial t^2} \approx \frac{1}{2}\frac{U_{k-1}^{l-1} - 2U_{k-1}^{l} + U_{k-1}^{l+1}}{\Delta t^2} + \frac{1}{2}\frac{U_k^{l-1} - 2U_k^{l} + U_k^{l+1}}{\Delta t^2},
\end{aligned}$$

where $\sigma = 0\ldots1$ is a weighting factor. This scheme is absolutely stable when $\sigma \geq 0.5$. Minimal integration error is provided at the lowest possible values of the weighting factor. However, in view of equation (2) with respect to the other members of the transport equation, those can cause instability of the scheme, if σ is close to the lower limit value.

On the other hand, considering that the order of the approximation of the template in Fig. 2 (b) does not depend on σ, it can be chosen the weighting factor of one. The corresponding pattern is shown in Fig. 2 (c) and the respective approximation on the longitudinal coordinate is of the form:

$$\frac{\partial U_{k-0,5}^{l}}{\partial z} \approx \frac{1}{2}\frac{U_k^{l-1} - U_{k-1}^{l-1}}{\Delta z} + \frac{1}{2}\frac{U_k^{l+1} - U_{k-1}^{l+1}}{\Delta z}.$$

The relationship between even and odd layers in this scheme is carried out only through the second derivative with respect to time. Such “splitting” can, in principle, be a source of instability. Although this has not been observed in practice, for the reliability, it is better to take the value of $\sigma = 2/3$.

In view of the smallness of the damping coefficient, the described above calculation method for $U_{k-0,5}^{l}$ magnitude is not critical. It can be calculated, for example, as the average of the amplitude values in the pattern corners or all its six points. Integration of (2) at each time step is carried out in the usual for the boundary problems manner, i.e., from input to output of the line. The initial conditions may be taken of zero. Dimensions of the steps Δt and Δz are unimportant as long as they are much less comparing with the respective spatio-temporal characteristics of the radio pulse envelope.

The modeling of radio pulse propagation in the “cold” regular electrodynamic system was performed. Stability of the algorithm and qualitative agreement between the numerical and analytic results confirm the correctness of (1) and (2), as well as their solutions based at the finite-difference schemes. The accuracy of solutions of generalized wave equations with a relative error less than 1 % is provided for non-harmonic signals with relative frequency bands up to 10 %.

The next stage of simulations must be solving the non-stationary self-consistent problem for the light-pumping cell by taking into account an actual dependence of the exciting current density $\vec{j}(t,x,y,z)$ from a non-equilibrium ensemble of radiating-absorbing atoms [8, 13].

V. CONCLUSION

A new construction of microwave-pumped optical laser with microwave-gained sulfur lamp as intermedium (source of optical pumping for the active element) was recently proposed. The advantages of such system are high efficiency, large reachable power, effective control of emitting light spectrum and inherent possibility in pulse operation. A general numerical model for the sulfur lamp excitation by short radio pulses of travelling or standing waves in regular line is described in this paper. The results may be useful for design and optimization of new constructions of optical quantum generators for civil and military purposes.

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