11

Generation of bright envelope solitons of subnanosecond duration in double negative bigyrotropic medium based on a magnetized ferromagnetic semiconductor film

© A.V. Bogomolova[1], D.V. Romanenko[1], S.V. Grishin[1], S.A. Nikitov[1,2]

[1] Saratov State University, Saratov, Russia
[2] Kotelnikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Moscow, Russia
E-mail: sergrsh@yandex.ru

Received July 15, 2024
Revised September 6, 2024
Accepted September 12, 2024

The results of numerical simulation of periodic sequences of bright envelope solitons of the sub-nanosecond duration in a film of bigyrotropic medium possessing properties of a ferromagnetic semiconductor are presented. Such short pulses are formed on a backward volume electromagnetic wave (BVEMW) existing at the frequencies where the medium material parameters are double negative. It is shown that the duration of bright envelope solitons on BVEMW is approximately two orders of magnitude shorter than that of bright envelope solitons which are formed on the backward volume magnetostatic spin wave in a ferromagnetic film.

Keywords: solitons, left-handed medium, ferromagnetic semiconductor.

DOI: 10.61011/TPL.2025.01.60150.20060

At present, one of the urgent issues of modern radiophysics and electronics is creation of sources of short and ultrashort pulses [1,2]. In the microwave range, a convenient medium for the formation of pulses in the form of bright envelope solitons is a ferromagnetic (FM) film exhibiting both the dispersion and nonlinearity (the latter manifests itself at the powers starting from tens of microwatts) [3,4]. In the FM film, there is observed propagation of magnetization waves known in literature as magnetostatic spin waves (MSWs) [5]. Durations of the MSW bright envelope solitons are about tens of nanoseconds [6]; the MSW dispersion characteristics and, hence, envelope solitons [7] are controlled, for instance, by using free charge carriers (electrons) existing either in the semiconductor (SC) layer [8,9] or in the metal layer [10–13] adjoining the FM film surface. Formation of the FM SC heterostructure enables additional (electrical) control of the bright MSW envelope solitons via the electron-induced variation in the slope of MSW dispersion characteristic [14]. However, the electronsínfluence on magnetization does not lead here to broadening of the frequency band of the MSW existence. The last circumstance prevents obtaining bright envelope solitons of a shorter (subnanosecond) duration.

In view of controlling the soliton modes, attractive are bi-gyrotropic media exhibiting both ferromagnetic and semiconductor properties [15,16]. In [15], an electrodynamic model of a bi-gyrotropic medium with the FM SC properties was proposed for the first time; this model accounted for the effect of free charge carriers in the form of plasma, as well as of exchange interaction, on the spectrum of electromagnetic waves existing in solids. Authors of [17] have shown that the effect of free charge carriers (electrons) on magnetization of the bi-gyrotropic medium with the FM SC properties leads to the fact that effective electric permittivity and magnetic permeability of the medium simultaneously become negative in a certain frequency range where the backward volume electromagnetic wave (BVEMW) arises. The BVEMW frequency bandwidth depends on the external dc magnetic field strength and direction, electron concentration in the magnetized plasma, saturation magnetization, and FM SC layer thickness. However, at certain electron concentrations (other magnetic subsystem parameters being equal), the BVEMW frequency bandwidth can significantly exceed that of MSW.

This paper demonstrates the formation of bright MSW envelope solitons with the subnanosecond duration which is shorter than that in the case of bright MSW envelope solitons existing in FM films.

Fig. 1, *a* represents schematically a transversely magnetized bi-gyrotropic medium layer adjoining on both sides ideally conducting metal planes. Electrical properties of such a medium are defined by those of a single-component (electron) cold collisionless magnetized plasma. In the case of the TE modes electromagnetic waves existing in a transversely magnetized bi-gyrotropic medium layer, the dispersion equation (DE) has the following form [17]:

$$k_x^2 + k^2 = k_0^2 \varepsilon_{eff\perp}^{\mathrm{TE}} \mu_{eff\perp}^{\mathrm{TE}}, \tag{1}$$

where $k_x = n\pi/d$ is the transverse wave number, d is the layer thickness, $n = \pm 1, 2, 3\ldots$ is the volume mode number of the TE electromagnetic wave, k is the longitudinal wave number, $k_0 = \omega/c$ is the vacuum wave number, $\omega = 2\pi f$ is the external-impact cyclic frequency, f is the external-impact linear frequency, c is the free-space light

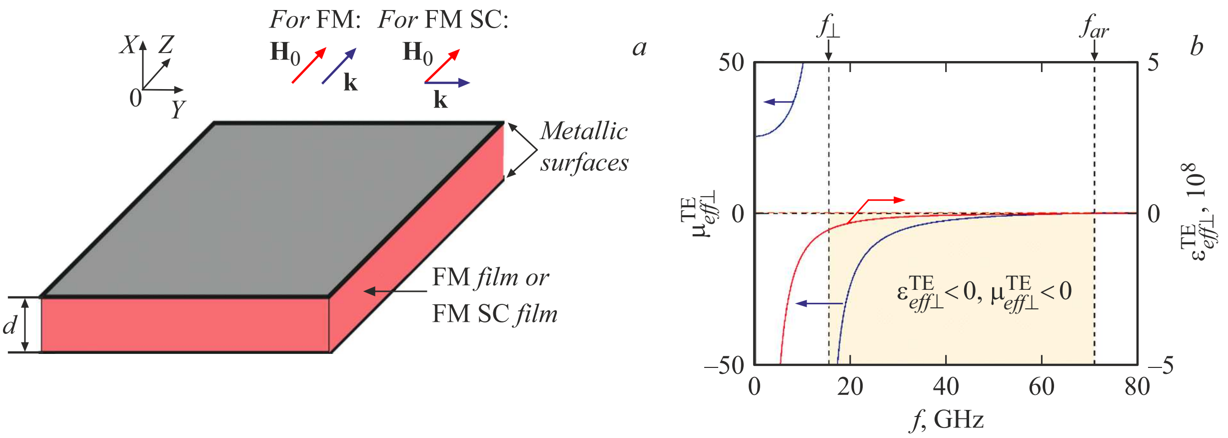

Figure 1. *a* — schematic representation of a transversely magnetized both-side-metallized FM SC layer, and also of a longitudinally magnetized both-side-metallized FM layer. *b* — frequency dependences of the effective high-frequency electric permittivity and magnetic permeability of the bi-gyrotropic medium with the FM SC properties. Calculations were performed for europium monoxide with $N = 10^{25}\,\mathrm{m}^{-3}$, $H_0 = 79.5775\,\mathrm{kA/m}$, and $4\pi M_0 = 2.43\,\mathrm{T}$ and $\varepsilon_r = 16$.

speed,

$$\varepsilon^{\mathrm{TE}}_{eff\perp} = \varepsilon_r \eta, \quad \mu^{\mathrm{TE}}_{eff\perp} = (\mu^2 - \mu_a^2)/\mu, \tag{2}$$

$\eta = 1 - \omega_{pe}^2/\omega^2$ is one of the diagonal components of the magnetic permeability tensor ε_r is the relative dielectric constant of the medium, $\mu = (\omega_\perp^2 - \omega^2)/(\omega_\parallel^2 - \omega^2)$ and $\mu_a = \omega_M\omega/(\omega_\parallel^2 - \omega^2)$ are the diagonal and non-diagonal components of the magnetic permeability tensor $\omega_\perp = \sqrt{\omega_\parallel \omega_{ar}}$ is the FM-resonance cyclic frequency in the case of the transverse magnetization, $\omega_{ar} = \omega_\parallel + \omega_M$ is the FM-antiresonance cyclic frequency, $\omega_\parallel = \gamma H_0$ is the FM-resonance cyclic frequency in the case of longitudinal magnetization, H_0 is the external dc magnetic field, $\omega_M = 4\pi\gamma M_0$, γ is the gyromagnetic ratio, $4\pi M_0$ is the medium saturation magnetization, $\omega_{pe} = \sqrt{4\pi N e^2/m_e}$ is the cyclic frequency of plasma electrons, N is the electron concentration in plasma, e/m_e is the electron specific charge.

Fig. 1, *b* presents frequency dependences of the effective permittivity and permeability calculated based on (2). The results presented show that, if the plasma electron frequency is higher than all the magnetic subsystem characteristic frequencies, then there is a frequency range $\omega_\perp < \omega < \omega_{ar}$ where $\varepsilon^{\mathrm{TE}}_{eff\perp}$ and $\mu^{\mathrm{TE}}_{eff\perp}$ are negative simultaneously.

Fig. 2, *a* presents the BVEMW dispersion characteristic (DC) calculated via (1) and (2) for the both-side-metallized bi-gyrotropic medium film with the properties of europium monoxide (EuO). The EuO parameters were taken from [18]. One can see that BVEMW exists in the frequency band where $\varepsilon^{\mathrm{TE}}_{eff\perp} < 0$ and $\mu^{\mathrm{TE}}_{eff\perp} < 0$. Note that in the transversely magnetized both-side-metallized FM film slow volume TE waves do not exist in the absence of free charges ($N = 0$). For comparison, Fig. 2 *b* demonstrates DC of the backward volume MSW (BVMSW) calculated in the magnetostatic approximation for the longitudinally magnetized ($\mathbf{H}_0 \parallel \mathbf{k} \parallel 0Z$) yttrium-iron garnet film. The BVMSW DC was calculated using the well-known dispersion equation [5]:

$$\mu k_x^2 + k^2 = 0. \tag{3}$$

The calculations presented show that BVMSW exists in the lower frequency band $\omega_\parallel < \omega < \omega_\perp$ where only the high-frequency magnetic permeability of the medium is negative ($\mu < 0$). Results of comparing DC characteristics of two backward waves indicate that the frequency band of BVEMW existing in the EuO film is 27 times longer than that of BVMSW existing in the yttrium-iron garnet film at the same film thickness and magnetic field strength.

It is known that nonlinearity of FM films is caused by the dependence of the magnetization vector longitudinal component on the squared field amplitude [5]. In this case, frequency ω_M depends on the squared field amplitude, and this dependence is different for different magnetization types (normal and tangential to the film surface). In the case of the FM film tangential magnetization, the dependence is as follows [5]:

$$\omega_M = 4\pi\gamma M_0\left[1 - \left(1 + \frac{\omega_\parallel^2}{\omega_\perp^2}\right)\frac{|\varphi|^2}{2}\right]. \tag{4}$$

For the FM SC film, only magnetic subsystem nonlinearity will be taken into account, since nonlinearity of the electrical subsystem begins being observed at large field amplitudes. It may be taken into account later, as, for instance, in [19].

To obtain the nonlinear Schrödinger equation (NSE) that describes the envelope amplitude evolution in a nonlinear dispersive medium, the „envelope“ method [5] is used, which is applicable both to the nonlinear DE in the form of (3) taking into account (4) and to the nonlinear DE in the form of (1) taking into account (2) and (4). In this case, NSE obtained for the slow BVEMW and BVMSW amplitudes will have a similar form:

$$j\left(\frac{\partial}{\partial t} + V_g\frac{\partial}{\partial r}\right)\varphi + \frac{\beta}{2}\frac{\partial^2\varphi}{\partial r^2} - \chi|\varphi|^2\varphi = 0, \tag{5}$$

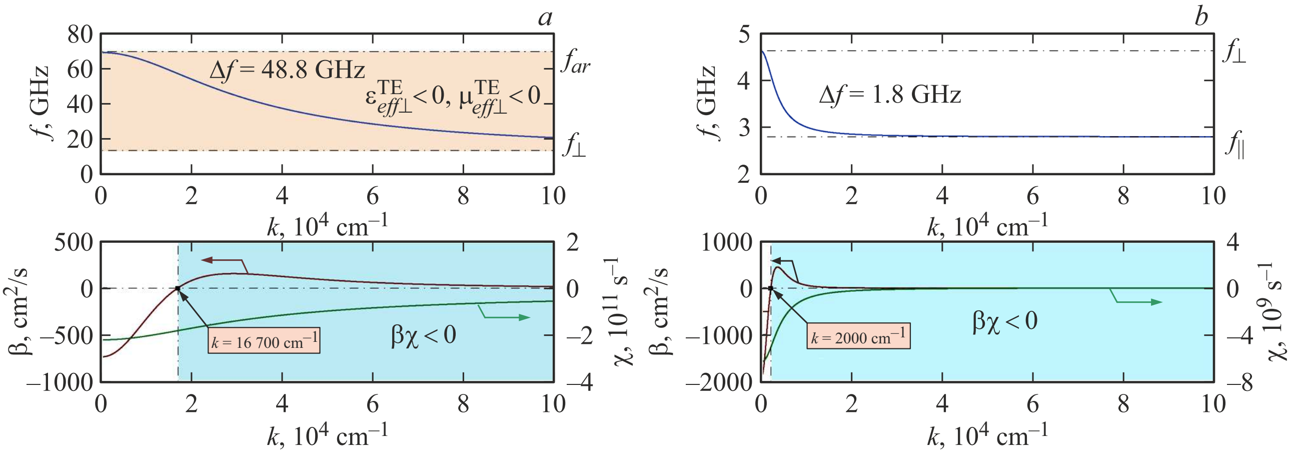

Figure 2. *a* — dispersion characteristic of BVEMW existing in the transversely magnetized FM SC film (top panel), and dependences of the BVEMW dispersion coefficients β and nonlinearity χ on the longitudinal wave number (bottom panel). *b* — dispersion characteristic of BVMSW existing in the longitudinally magnetized FM film (top panel), and dependences of the BVMSW dispersion coefficients β and nonlinearity χ on the longitudinal wave number (bottom panel). For the FM SC film, $N = 10^{25}\,\mathrm{m}^{-3}$ and $4\pi M_0 = 2.43\,\mathrm{T}$. For the FM film, $4\pi M_0 = 0.175\,\mathrm{T}$. In both cases, $H_0 = 79.5775\,\mathrm{kA/m}$, $d = 10^{-5}\,\mathrm{m}$, $n = 1$ and $\varepsilon_r = 16$.

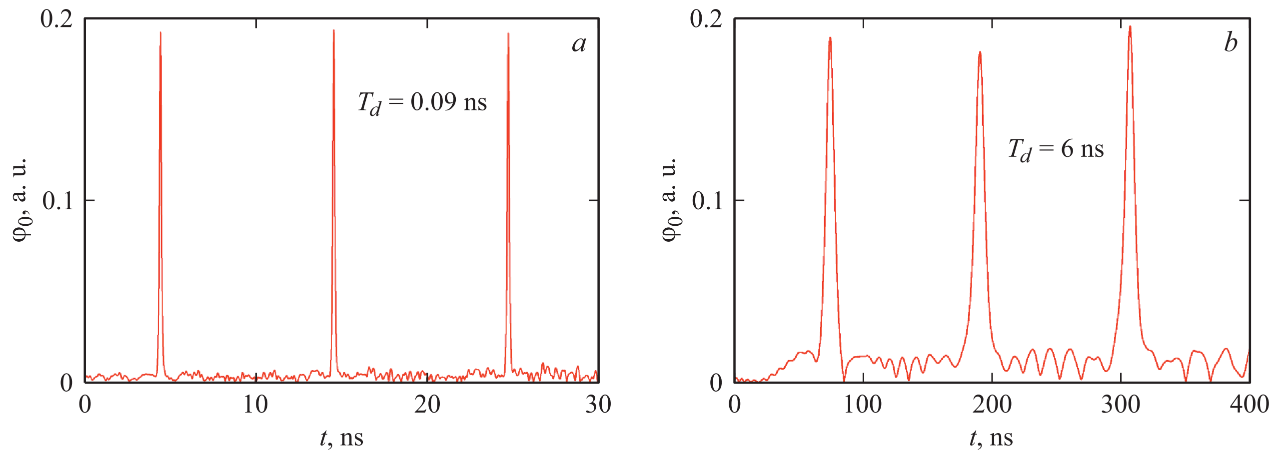

Figure 3. Periodic sequences of bright soliton-like pulses on BVEMW (*a*) and BVMSW (*b*). *a* — calculations for $N = 10^{25}\,\mathrm{m}^{-3}$, $4\pi M_0 = 2.43\,\mathrm{T}$, $V_g = -5.209 \cdot 10^4\,\mathrm{m/s}$, $\beta = 154.5 \cdot 10^{-4}\,\mathrm{m^2/s}$, $\chi = -1.373 \cdot 10^{11}\,\mathrm{s}^{-1}$; *b* — for $4\pi M_0 = 0.175\,\mathrm{T}$, $V_g = -8.651 \cdot 10^3\,\mathrm{m/s}$, $\beta = 280.9 \cdot 10^{-4}\,\mathrm{m^2/s}$, $\chi = -2.155 \cdot 10^9\,\mathrm{s}^{-1}$. *b* — for $4\pi M_0 = 0.175\,\mathrm{T}$, $V_g = -8.651 \cdot 10^3\,\mathrm{m/s}$, $\beta = 280.9 \cdot 10^{-4}\,\mathrm{m^2/s}$, $\chi = -2.155 \cdot 10^9\,\mathrm{s}^{-1}$. In both cases, $H_0 = 79.5775\,\mathrm{kA/m}$, $d = 10^{-5}\,\mathrm{m}$, $n = 1$ and $\varepsilon_r = 16$.

where $r = y$ in the case of transverse magnetization, $r = z$ in the case of longitudinal magnetization (see Fig. 1, *a*), φ is the dimensionless slow amplitude of either BVEMW or BVMSW, $\beta = \partial^2\omega/\partial k^2$ is the group-velocity dispersion (dispersion coefficient), $\chi = \partial\omega/\partial|\varphi|^2$ is the nonlinearity coefficient. The only NSE coefficients which will be different for BVEMW and BVMSW are V_g, β and χ. NSE in the form given in (5) can describe processes associated with the development of modulation instability in the medium. Development of the modulational instability with respect to longitudinal disturbances gives rise to the bright envelope solitons. In this case, the Lighthill criterion should be met:

$$\beta\chi < 0. \tag{6}$$

Fig. 2, *a, b* shows also the dependences of the dispersion and nonlinearity coefficients of two backward volume waves on the longitudinal wave number. For both media, criterion (6) gets satisfied starting from a certain value of the longitudinal wave number. For instance, this value for the FM PP film is $k = 167 \cdot 10^4\,\mathrm{m}^{-1}$, while that for the FM film is $k = 20 \cdot 10^4\,\mathrm{m}^{-1}$.

Fig. 3 presents calculations of the periodic sequences of bright envelope solitons obtained by numerically solving NSE (5) under periodic boundary conditions. With this consideration, the BVEMW/BVMSW envelope amplitude may be loss-less transferred from the system output to input, which is similar to the case of an active ring resonator whose gain completely compensates for the BVMSW/BVEMW propagation losses. Soliton solutions were obtained both for BVEMW with $k = 300 \cdot 10^4\,\mathrm{m}^{-1}$ (Fig. 3, a) and BVMSW with $k = 55 \cdot 10^4\,\mathrm{m}^{-1}$ (Fig. 3, b). One can see that duration of the bright envelope solitons on BVEMW is $T_d = 90$ ps, while that of the bright envelope solitons on BVMSW is $T_d = 6$ ns. Thus, duration of the bright envelope solitons on BVEMW is approximately two orders of magnitude shorter than that on BVMSW. This fact has found confirmation in examining the well-known analytical solution of NSE (5) obtained for a bright envelope soliton [20]. From the analytical solution it follows that, provided the bright envelope soliton amplitude is constant, its duration is directly proportional to β and inversely proportional to χ. In our case, the increase in χ of BVEMW by two orders of magnitude compared to χ of BVEMW with slightly changing β causes a significant decrease in duration of the bright BVEMW envelope soliton.

The obtained results may be of interest in developing short pulse sources for magnonic logic systems and neuromorphic computing [21].

Funding

The study was supported by the Russian Science Foundation (project
No 23-79-30027).

Conflict of interests

The authors declare that they have no conflict of interests.

References

[1] N.S. Ginzburg, G.G. Denisov, M.N. Vilkov, A.S. Sergeev, S.V. Samsonov, A.M. Malkin, I.V. Zotova, Phys. Rev. Appl., **13** (4), 044033 (2020).
DOI: 10.1103/PhysRevApplied.13.044033

[2] A.S. Bir, S.V. Grishin, O.I. Moskalenko, A.N. Pavlov, M.O. Zhuravlev, D. Osuna Ruiz, Phys. Rev. Lett., **125** (8), 083903 (2020). DOI: 10.1103/PhysRevLett.125.083903

[3] T. Eguchi, M. Kawase, K. Sekiguchi, Appl. Phys. Express, **15** (8), 083001 (2022). DOI: 10.35848/1882-0786/ac7ead

[4] A.V. Kondrashov, A.B. Ustinov, J. Appl. Phys., **132** (17), 173907 (2022). DOI: 10.1063/5.0123442

[5] A.V. Vashkovsky, V.S. Stalḿakhov, Yu.P. Sharaevsky, *Magnitostaticheskie volny v elektronike sberkhvysokikh chastot* (Izd-vo SGU, Saratov, 1993). (in Russian)

[6] M. Wu, Solid State Phys., **62**, 163 (2010).
DOI: 10.1016/B978-0-12-374293-3.00003-1

[7] A.S. Kindyak, A.D. Boardman, V.V. Kindyak, J. Magn. Magn. Mater., **253** (1-2), 8 (2002).
DOI: 10.1016/S0304-8853(01)00195-0

[8] M.A. Morozova, D.V. Romanenko, A.A. Serdobintsev, O.V. Matveev, Y.P. Sharaevskii, S.A. Nikitov, J. Magn. Magn. Mater., **514** (15), 167202 (2020).
DOI: 10.1016/j. jmmm.2020.167202

[9] A.V. Sadovnikov, E.N. Beginin, S.E. Sheshukova, Y.P. Sharaevskii, A.I. Stognij, N.N. Novitski, V.K. Sakharov, Y.V. Khivintsev, S.A. Nikitov, Phys. Rev. B, **99** (5), 054424 (2019). DOI: 10.1103/ PhysRevB.99

[10] A.A. Nikitin, A.A. Nikitin, A.B. Ustinov, A.E. Komlev, E. Lähderanta, B.A. Kalinikos, J. Appl. Phys., **128** (18), 183902 (2020). DOI: 10.1063/5.0027792

[11] S. Mae, R. Ohshima, E. Shigematsu, Y. Ando, T. Shinjo, M. Shiraishi, Phys. Rev. B, **105** (10), 104415 (2022). DOI: 10.1103/PhysRevB.105.104415

[12] R.O. Serha, D.A. Bozhko, M. Agrawal, R.V. Verba, M. Kostylev, V.I. Vasyuchka, B. Hillebrands, A.A. Serga, Adv. Mater. Interfaces, **9** (36), 2201323 (2022).
DOI: 10.1002/admi.202201323

[13] A. Krysztofik, N. Kuznetsov, H. Qin, L. Flajšman, E. Coy, S. van Dijken, Materials, **15** (8), 2814 (2022).
DOI: 10.3390/ma15082814

[14] A.S. Kindyak, ZhTF, **64** (11), 99 (1994). (in Russian)

[15] M. Stil, B. Vyural; *Vzaimodeystvie voln v plasme tverdogo tela* (Atomizdat, M., 1973). (in Russian)

[16] A.G. Gurevich, G.A. Melkov, *Magnitnye kolebaniya i volny* (Fizmatlit, M., 1994). (in Russian)

[17] A.V. Bogomolova, F.Yu. Ogrin, S.A. Nikitov, S.V. Grishin, J. Magn. Magn. Mater., **587**, 171278 (2023).
DOI: 10.1016/j.jmmm.2023.171278

[18] A.S. Borukhovich, A.V. Troshin, *Poluprovodnik i ferromagnetic monooksid evropiya v spintronike* (Lan; SPb., 2017). (in Russian)

[19] M.A. Cherkasskii, B.A. Kalinikos, Tech. Phys. Lett., **39** (2), 182 (2013). DOI: 10.1134/S1063785013020065.

[20] Yu.S. Kivshar; G.P. Agraval, *Opticheskie solitony: ot svetovodov k fotonnym kristallam* (Fizmatlit, M., 2005). (in Russian)

[21] S. Watt, M. Kostylev, A.B. Ustinov, B.A. Kalinikos, Phys. Rev. Appl., **15** (6), 064060 (2021).
DOI: 10.1103/PhysRevApplied.15.064060

Translated by EgoTranslating