Conclusion

A complex of fundamental and applied, theoretical and experimental studies of wave processes in magneto arranged film structures in the millimeter range of radio waves has been carried out. The following basic scientific problems have been solved:

- Electromagnetic wave excitation and reception in multilayered bigyrotropic structures screened with impedance surfaces, without any restriction by losses, their cross-section distribution, the distribution of electric and magnetic parameters
- Electromagnetic wave propagation in multilayered bigyrotropic structures in flat waveguides and at unilateral metallization with impedance surfaces
- Nondestructive measurements of the basic dissipative and magnetic parameters of film ferrites within the UHF and EHF ranges
- Development of the radiophysical basis for the design of millimeter-range magnetoelectronic devices

The following results have been obtained:

1. A generalized theory of electromagnetic wave excitation in multilayered structures screened with impedance surfaces with parallel and orthogonal orientations to the exciting plane has been developed to analyze the properties of magnetoelectronic converters and transmission lines made of layered bigyrotropic structures containing magnetized layers of ferrites, semiconductors, magnetic semiconductors, dielectrics, ferroelectrics and their various combinations in the UHF and EHF ranges.

2. The properties of microstrip, slot and waveguide converters with various orientations and magnetization of their structures made of ferrite films in the UHF and EHF ranges have been investigated theoretically and experimentally. It is shown that:
   - For selective excitation and reception of fast and slow electromagnetic waves near the resonant frequencies an enhanced uniformity of the exciting fields is required, which is most simply implemented at the orthogonal orientation of the structures to the exciting plane.
Microstrip converters are the most universal ones and allow both the broadband and narrow-band modes to be realized at excitation of fast and slow electromagnetic, and magnetostatic waves.

Slot converters provide excitation of the full spectrum of waves in the broadband modes and selective excitation of fast and slow electromagnetic waves near the resonant frequencies at the orthogonal orientation of the structure.

3. Most essential factors determining the principal features at excitation and propagation of waves near the resonant frequencies in the millimeter range have been revealed, namely:

- Reduction of the maximum values of the HF magnetic susceptibilities of the imaginary parts of both the diagonal and off-diagonal components \( \chi''_r = \frac{M_S}{2\Delta H(\nu)} \) and the real part of the diagonal component \( \chi'_r = \frac{M_S}{2\Delta H_0} \)
- Losses in the layers and a rise of their cross gradients at higher frequencies
- Cross gradients of the static electric and magnetic parameters
- Back influence of the excited waves in the structures on the source fields
- A more important role of metal screens

4. Our experiments have shown waveguide and strip converters, and transmission lines made of ferrite films to provide an expanded dynamic range of the linear mode up to several tens watt of continuous and average powers in the pulse modes.

5. A significant excess of the band of waves of various types excited by strip and waveguide converters in both the broadband and narrow-band modes and ducted in ferrite-dielectric layered structures with a low level of ferromagnetic losses \( (\alpha < 10^{-4}) \) over the band determined from the MSW approximation has been experimentally found and theoretically confirmed. The same applies to an essential linear shift of the lower frequency border of the MSW approximation from which the model of dipole–dipole interactions is valid towards higher wave numbers \( (\kappa > 50 - 100 \text{ rad/cm}) \) at advance into the millimeter range.

6. Selective processes at excitation and propagation of various wave types in arbitrary magnetized structures based on weakly dissipative ferrite films \( (\alpha < 10^{-3} \div 10^{-4}) \) in ranges near the resonant frequencies have been shown, theoretically and experimentally, to be described by a two-wave model to determine:

- The effects of selective signal attenuation at interference of fast and slow electromagnetic waves, signal transmission by slow waves in structures with an absorbing covering, selective directed power branching by the structure, selective phase inversion on the fast, slow, or both waves in an antiphase balanced circuit (in the pre-limit mode)
- The effects of transmission under concurrence of fast and slow waves depending on the frequency range (in the post-limiting/beyond-cutoff mode)
7. On the basis of the selective effects of fast and slow electromagnetic wave excitation in layered structures with ferrite films (including multilayered ones) the following types of sensors have been designed:

- Sensors of the resonant frequencies for structures with arbitrary magnetization
- Sensors of external and internal magnetic fields to provide an accuracy and spatial resolution two or three orders of magnitude higher in comparison with semiconductor Hall sensors

8. New methods and devices of nondestructive estimation of the following key parameters of ferrite film structures have been developed: FMR line width, cross gradients of saturation magnetization, anisotropy field, and internal field. These devices are based on the effects of selective absorption and propagation of fast and slow waves, discrete and continuous sounding of the structures with various types of magnetostatic and weakly-delayed electromagnetic waves with solid and surface distributions of fields, the delay time dispersion of signals in a boundary field.

9. Physical principles of the design of magnetoelectronic devices of low and high power levels have been developed, they include:

- Design and optimization of converters
- Design of transmission lines with required dispersions
- Design of miniature magnetic systems with a heatset, high-speed electric and discrete mechanical field reorganization
- Devices for coordination with waveguides
- Ways to reduce the irregularity and shape of AFC
- Increasing the electric strength of devices

10. A new class of controllable magnetoelectronic devices on the basis of ferrite films in the millimeter range of low and high power levels has been developed, namely:

- Single-channel and multichannel band-transmitting and band-blocking filters, including preselectors with high-speed reorganization and small introduced losses of LPL and HPL
- Controllable lines for signal delay with decreasing, increasing, and weakly dispersive dependencies
- A miniature multichannel receiver for direct amplification

11. There are some promising leads in the field of EHF magnetoelectronics, namely:

- EHF magnetooptics
- Non-linear processes at increased levels of the continuous and pulse power in the EHF range
- Design of active devices of LPL and HPL on the basis of EHF magnetoelectronic elements
– Processes in structures with HTSC
– Electromagnetic radiation scattering on finite-sized ferrite-dielectric structures
– Design of controllable solid-state PA.
Appendix 1

Tensors $\mu_n$ and $\varepsilon_n$ of the magnetic field $\mathbf{H}_0$:

- In the OZ direction

$$
\begin{pmatrix}
\mu_{Tn} & j\mu_{Nn} & 0 \\
-j\mu_{Nn} & \mu_{Tn} & 0 \\
0 & 0 & \mu_{Ln}
\end{pmatrix}, \quad
\begin{pmatrix}
\varepsilon_{Tn} & j\varepsilon_{Nn} & 0 \\
-j\varepsilon_{Nn} & \varepsilon_{Tn} & 0 \\
0 & 0 & \varepsilon_{Ln}
\end{pmatrix}
$$

(Ap. 1a)

- In the OX direction

$$
\begin{pmatrix}
\mu_{Ln} & 0 & 0 \\
0 & \mu_{Tn} & j\mu_{Nn} \\
0 & -j\mu_{Nn} & \mu_{Ln}
\end{pmatrix}, \quad
\begin{pmatrix}
\varepsilon_{Ln} & 0 & 0 \\
0 & \varepsilon_{Tn} & j\varepsilon_{Nn} \\
0 & -j\varepsilon_{Nn} & \varepsilon_{Ln}
\end{pmatrix}
$$

(Ap. 1b)

- In the OY direction

$$
\begin{pmatrix}
\mu_{Tn} & 0 & j\mu_{Nn} \\
0 & \mu_{Ln} & 0 \\
-j\mu_{Nn} & 0 & \mu_{Tn}
\end{pmatrix}, \quad
\begin{pmatrix}
\varepsilon_{Tn} & 0 & j\varepsilon_{Nn} \\
0 & \varepsilon_{Ln} & 0 \\
-j\varepsilon_{Nn} & 0 & \varepsilon_{Tn}
\end{pmatrix}
$$

(Ap. 1c)

Given losses, the components of the tensors $\mu_n$ and $\varepsilon_n$ are complex with:

- Their diagonal components

$$
\mu_{Tn} = \mu_{Tn}' - j\mu_{Tn}'', \quad \varepsilon_{Tn} = \varepsilon_{Tn}' - j\varepsilon_{Tn}''
$$

- Their off-diagonal components

$$
\mu_{Nn} = \mu_{Nn}' - j\mu_{Nn}'', \quad \varepsilon_{Nn} = \varepsilon_{Nn}' - j\varepsilon_{Nn}''
$$

Given low losses in the ferrite ($\alpha_n << 1$), the components of $\mu_n$ are
where

\[
\begin{align*}
\mu_{Tn} &= \{(1 + \alpha_n^2) \omega_H^2 - \omega^2 \} \cdot (\mu_0 - 1) + 4 \alpha_n^2 \mu_0 \omega^2 \omega_H \} D^{-1}, \\
\mu''_{Tn} &= \{(1 - \alpha_n^2) \omega_H^2 - \omega^2 \} \cdot \gamma M_{sn} D^{-1}, \\
\mu''_{Nn} &= 2 \alpha_n \omega \omega_H D^{-1}, \\
\mu''_{Nn} &= \{(1 + \alpha_n^2) \omega_H^2 + \omega^2 \} \cdot \alpha_n \omega_H D^{-1}, \\
D &= \mu_0 \{(1 + \alpha_n^2) \omega_H^2 - \omega^2 (4 \alpha_n^2 - \omega_H^2) - 1 \}, \\
\omega_n &= \gamma (H_{0i})_n,
\end{align*}
\]

\( \gamma \) – gyromagnetic ratio \((\gamma < 0)\),
\( H_{0i} \) – internal field intensity,
\( \alpha_n = (\Delta H / H_{0i})_n \) – phenomenological parameter of ferromagnetic losses,
\( \Delta H \) – line width of ferromagnetic resonance,
\( \omega \) – signal frequency,
\( M_{sn} \) – saturation magnetization,
\( \mu_0 \) – magnetic constant \((\mu_0 = 4\pi \cdot 10^{-7} \text{H/m})\).

For polar semiconductors with free charge carriers in a magnetic field \(H_{0i} \parallel OZ\) such a model is used in which a dielectric lattice constant \(\epsilon_{cn}\) independent of frequency and magnetic field is introduced, and

\[
\begin{bmatrix}
\epsilon_Tn + \epsilon_{cn} \\
j\epsilon_{Nn} \\
\epsilon_{Ln} + \epsilon_{cn}
\end{bmatrix} =
\begin{bmatrix}
\epsilon_{Tn} + \epsilon_{cn} & j\epsilon_{Nn} & 0 \\
-j\epsilon_{Nn} & \epsilon_{Tn} + \epsilon_{cn} & 0 \\
0 & 0 & \epsilon_{Ln} + \epsilon_{cn}
\end{bmatrix},
\]

Ap. 3

where

\[
\begin{align*}
\epsilon'_{Tn} &= \epsilon_{cn} + \omega_{pn} \left( \omega_{cn}^2 - \omega^2 - \omega_{cn}^2 \right) F^{-1}_{en}, \\
\epsilon''_{Tn} &= \omega_{pn} \left( 2 \omega_{cn}^2 - 3 \omega^2 \right) \omega_{cn}^2 F^{-1}_{en}, \\
\epsilon''_{Nn} &= -2 \omega_{pn} \omega_{cn} \omega_{cn}^2 F^{-1}_{en}, \\
\epsilon''_{Nn} &= \omega_{pn} \left( \omega_{cn}^2 \omega_{cn}^2 - \omega^2 \omega_{cn}^2 + \omega_{cn}^4 \right) F^{-1}_{en}, \\
\epsilon''_{Ln} &= \epsilon_{cn} - \omega_{pn} \omega_{cn}^2 F^{-1}_{en}, \\
\epsilon''_{Ln} &= \omega_{pn} \omega_{cn} \omega_{cn}^2 F^{-1}_{en}, \\
F_{en} &= \omega_{cn} \left( 1 + 4 \omega^2 \right) - \omega^2 + \omega_{cn}^2, \\
\omega_{pn} &= \frac{e_{0n} n}{\epsilon_0 m^*_n}, \\
\omega_{cn} &= \frac{1}{\tau_n} \text{ – plasma frequency,} \\
\omega^*_c &= \frac{qB}{\epsilon_0 m^*_n} \text{ – collision rate,} \\
n_n \text{ – electron concentration,} \\
B \text{ – magnetic induction,} \\
e_{0n} \text{ – electron charge,} \\
\tau_n \text{ – free path time,} \\
m_n^* \text{ – effective mass.}
\]
Appendix 2

Estimation of Gelder’s parameters for the difference $|f(\xi) - f(\xi^T)|$.

For $f(\xi) = e^{-j\frac{K_0 w}{2} \xi \sqrt{1 - \xi^2}}$, $f(\xi^T) = e^{-j\frac{K_0 w}{2} \xi^T t \sqrt{1 - (\xi^T)^2}}$

$$|f(\xi) - f(\xi^T)| = \left| e^{-j\frac{K_0 w}{2} \xi \sqrt{1 - \xi^2}} - e^{-j\frac{K_0 w}{2} \xi^T \sqrt{1 - (\xi^T)^2}} - 2\xi e - e \right|$$

$$\leq \left| 1 - e^{-j\frac{K_0 w}{2} \xi \sqrt{1 - \xi^2}} \right| \leq \frac{1}{2} \epsilon^2.$$ 

So, Gelder’s parameters are:

$$A = \frac{1}{2}, \quad \lambda = 2.$$  

(Ap. 4)
Appendix 3

Solution of the non-uniform integral second-type Fredholm equation with an expressed kernel.

After multiplication of Eq. (1.130) by $e^{i \frac{K_w}{2} \sin t}$ and integration over the range $(-\pi/2, \pi/2)$, we have $x(t^T) = B + E \cdot x(t^T) \cdot D$, where

$$x(t^T) = \int_{-\pi/2}^{\pi/2} J(t^T) e^{i \frac{K_w}{2} \sin t^T} dt^T,$$

$$B = \int_{-\pi/2}^{\pi/2} e^{i \frac{K_w}{2} \sin t} dt,$$

$$D = \int_{-\pi/2}^{\pi/2} e^{i \frac{K_w}{2} \sin t} \left[ e^{-i \frac{K_w}{2} \sin t} \cos t \cdot \ln \frac{1 - \sin t}{1 + \sin t} - \sin t \right] dt.$$

Then, from Eq. (Ap. 5) we get

$$x(t^T) = \frac{B}{1 - ED}. \quad \text{(Ap. 6)}$$

Substitution of Eq. (Ap. 6) into Eq. (1.130) produces

$$J(t) = 1 + E \left[ e^{-i \frac{K_w}{2} \sin t} \cos t \cdot \ln \frac{1 - \sin t}{1 + \sin t} - \sin t \right] \cdot \frac{B}{1 - ED}. \quad \text{(Ap. 7)}$$
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