1. Introduction

In modern science, medical applications related to (i) magnetic separation,4 (ii) targeted drug delivery to diseased tissues,4 (iii) the creation of new MRI contrast agents working at the cellular and molecular level for tumor theranostics,5,6 (iv) tissue engineering and regenerative medicine,5,6 (v) magnetic hyperthermia7,8 are of great interest. In each of these applications, a unique combination of the properties for magnetic nanoparticles (MNPs) is to have a small size and to generate heat under an alternating magnetic field (AMF). The MNP size is in the range of ~1–100 nm, which is comparable with the sizes of intracellular biological structures of ~10–100 nm, viruses ~10–200 nm, proteins ~4–50 nm and genes ~2–100 nm.9 This allows MNP to penetrate into the tissue and affect the physiological processes of the body at the cellular level. The intensity of heating depends both on the properties of the magnetic nanomaterial (dispersion, Curie temperature, coercivity, magnetization), and on the characteristics of the external influence (temperature, exposure time, AMF amplitude and frequency). While local heating above 44 °C, necrosis of muscle tissue occurs in 10 min.10 To avoid overheating, it is necessary to strictly control exposure time, AMF amplitude and nanoparticle concentration.11 The risk of tissue overheating is minimized by the intelligent control system for magnetic hyperthermia. The work of the intelligent system is based on the fact that the Curie temperature of the particles is in the safe hyperthermia range of 42–44 °C. Above the Curie temperature, the particle goes into the paramagnetic (PM) state and its heating ceases. Such a nanopowder exhibits the properties of a smart nanomaterial, since it automatically changes its properties depending on external conditions.

The synthesis of such smart nanopowder allows us to solve another complex problem that is associated with intracellular (local) hyperthermia.12,13 In magnetic hyperthermia, heating of a particle occurs as a result of losses associated with both frictional heating of a particle during its rotation under AMF (Brownian relaxation) and relaxation of magnetization without rotation of the particle (Néel relaxation).14 In intracellular hyperthermia, a particle via the core–shell structure is modified
with biocompatible agents and is rigidly attached to the protein structures of the cell. The rotation of such a particle under AMF can lead to mechanical damage and cell death. In order to avoid mechanical damage to cell structures, heating should be carried out only as a result of Néel relaxation. The temperature dependence of the specific loss power (SLP) during the Néel relaxation has a resonant form and increases sharply near the temperature of the magnetic phase transition. Since, the Curie temperature of smart magnetic nanopowder is in the hyperthermia range of 42–44 °C, such powder with the necessary set of magnetic properties can be used for local hyperthermia without the risk of mechanical damage to cell structures. The search for such smart magnetic nanopowder is a topical task for materials science, physics, nanomedicine and nanotechnology.

2. Heating mechanism and composition choice

In the magnetometric method, which is used to estimate the heating efficiency in hyperthermia, the SLP can be obtained from hysteresis losses during magnetization reversal. The hysteresis heating can be observed both in the quasi-stable hysteresis and in the relaxation hysteresis. The main difference in the heating mechanisms is that dissipative processes appear in the relaxation region, which are associated with the appearance of a phase difference between the AMF and magnetization. The SLP in single-domain (SD) particles under the AMF is significantly higher than in multidomain (MD) particles. Thus, it is advisable to use a magnetic powder, which should consist of SD soft MNPs with a large magnetization near FM transition temperature.

For SD monodisperse spherical particles in the quasi-stable region, the magnetostatic dependence of the specific hysteresis loss \( w_{sw} \) is approximated by the following expression:

\[
 w_{sw}(H) = \begin{cases} 
 0 & H \leq H_c \\
 4M_B H_c \left( 1 - \frac{H_c}{H} \right)^{0.5} & H > H_c 
 \end{cases}
\]

where \( M_B \) is the residual magnetization, \( H_c \) is the coercive field, and \( H \) is the magnetic field. The SLP in the external AMF is specified by multiplying the \( w_{sw} \) by the frequency \( f \) of the AMF:

\[
 SLP(H, f) = w_{sw}(H) \times f.
\]

Heating MNPs in the relaxation hysteresis is associated with the relaxation processes of magnetization. The relaxation time \( \tau_R \) for soft magnetic particles, which do not rotate and do not move in the AMF, is equal to the Néel relaxation time \( \tau_R = \tau_N = \tau_0 \exp(K_{eff}V/k_B T) \), where \( \tau_0 \sim 10^{-8} \text{ to } 10^{-11} \text{ s} \) is the characteristic relaxation time. On the hysteresis curves \( M(H) \), the inclination of the relaxation magnetization processes manifests itself in increasing the area of the hysteresis region \( A \), which has an ellipsoidal shape with an increase in the AMF frequency \( f \). In the magnetic hyperthermia for nanosystems with the parameter \( \sigma = K_{eff}V/k_B T \), the specific hysteresis loss \( w_{sw} \) in the relaxation region is calculated by the following expressions:

\[
 A = \frac{\pi H_{max}^2 M_s^2 V}{3k_B T \rho} \left( \frac{\omega \tau_R}{1 + \omega^2 \tau_R^2} \right), \quad \text{for } \sigma \ll 1, 
\]

\[
 A = \frac{\pi H_{max}^2 M_s^2 V}{k_B T \rho} \left( \frac{\omega \tau_R}{1 + \omega^2 \tau_R^2} \right), \quad \text{for } \sigma \gg 1, 
\]

where \( A \) is equal to \( w_{sw} \), \( H_{max} \) is the AMF amplitude, \( M_s \) is the saturation magnetization, \( V \) is the volume of the particle, \( \rho \) is the density, \( \omega = 2\pi f \) is the cyclic AMF frequency.

With an increase in the temperature, the heating efficiency of SLP in a quasi-stable hysteresis region decreases in proportion to the multiplication of \( M_s \) and \( H_c \) (see eqn (1) and (2)) and equals zero at \( T_C \). However, the SLP increases for the relaxation hysteresis near the temperature of the magnetic phase transition (see eqn (4)). This heating mechanism of particles to a Curie temperature is advisable to use as the main mechanism for heating magnetic nanoparticles in local hyperthermia. The search for a soft magnetic material with a Curie temperature \( t_C = 42–44 \text{ °C} \), a high saturation magnetization near the Curie temperature, and a narrow temperature FM–PM phase transition is a topical task for both hyperthermia and material science. Summarizing the above, it is possible to establish requirements for the choice of the composition and characteristics of nanopowder that can be used as a smart magnetic material for local hyperthermia: (i) the nanopowder should be a soft magnetic material, (ii) the magnetic nanoparticles should be predominantly in the SD state, (iii) the Curie temperature should be in the \( t_C = 42–44 \text{ °C} \) range, (iv) the nanopowder should have a narrow temperature range of the magnetic phase transition FM–PM, (v) the magnetic nanoparticles should have a large saturation magnetization \( M_s \) near \( t_C \), and (vi) the nanopowder should have a lower \( H_c \) coercivity with respect to the AMF \( (H_{max} > H_C) \).

This list of functional properties may be satisfied by rare-earth manganites La\(_{1-x}\)A\(_{x}\)Mn\(_3\)O\(_7\) with a perovskite structure ABO\(_3\), where \( A \) is a mono- or divalent large A-cation, such as La\(^{3+}\), Sr\(^{2+}\), Ba\(^{2+}\), Ca\(^{2+}\), Sr\(^{2+}\), Ba\(^{2+}\), K\(^{+}\), Na\(^{+}\), or Ag\(^{+}\). The Curie temperature of these compounds strongly depends on the ratio Mn\(_B\)\(^{3+}\)/Mn\(_A\)\(^{4+}\), so it is quite easy to control it by changing the concentration and valence state of the A-cation to obtain \( t_C = 42–44 \text{ °C} \).

Great difficulties in finding the magnetic material for local hyperthermia are connected with the fact that they should have a narrow temperature range of the FM–PM magnetic phase transition. An increase in the temperature range of the magnetic phase transition is associated with both the appearance of local antiferromagnetic interactions caused by the Jahn–Teller electron–phonon interaction with orthorhombic distortions, and the magnetic inhomogeneity of the local environment of manganese as a result of the presence of cation V\(^6\) and anion V\(^5\) vacancies. Superstoichiometric manganese is an excess manganese, for which the filling factor of the B-position in the molar formula exceeds one. Using NMR method, it was shown that superstoichiometric manganese, which fills cation vacancies and completes the B-sublattice of manganese, increases magnetic homogeneity and reduces the temperature range of magnetic ordering. It should be noted that among the compositions with super-stoichiometric manganese of La\(_{1-x}\)Mn\(_{1.3}\)O\(_{3-\delta}\),...
La₀.₇Sr₀.₃Mn₁.₁O₃⁴ La₀.₇Sr₀.₃–ₓBiₓMn₁.₁O₃,⁵ (La₀.₃C₀.₇)₁₋ₓMn₁+xO₇,⁶,⁷ (Nd₀.₃Sr₀.₇)₁₋ₓMn₁+xO₇–₄⁸ and La₀.₉₋ₓAgₓMn₁.₄O₃⁹ the Ag-containing manganites have a Curie temperature which most close to the necessary functional properties of the magnetic material for hyperthermia, i.e. Tc = 42–44 °C.⁴⁹ Therefore, the non-stoichiometric La₀.₆Ag₀.₂Mn₁.₂O₃ composition with an increased content of super-stoichiometric manganese is considered here as the basis for the production of smart magnetic nanopowder for local hyperthermia. In addition, on the toxicity of the investigated nanopowder, it should be added that the manganite perovskite nanoparticles show a better colloidal stability, good biocompatibility with cell lines and do not have toxic effects.⁵⁰

3. Methods

The pyrolytic synthesis of La₀.₆Ag₀.₂Mn₁.₂O₃ nanopowder was used. As initial components, aqueous solutions of lanthanum nitrate (0.5 mol L⁻¹), manganese nitrate (0.6 mol L⁻¹), and silver nitrate (0.1 mol L⁻¹) were used. The nitrate solutions were mixed in a stoichiometric ratio and evaporated in a water bath at 80 °C for 6 h. Pyrolysis of the dried mixture was carried out at 600 °C. After grinding in an agate mortar, the powder was calcined in an alumina crucible at 800 °C (10 h). Additional synthesizing annealing was performed at 900 °C (20 h). The powder was cooled under conditions of natural heat exchange between the furnace and the environment.

X-ray diffraction studies were performed on a Shimadzu LabX XRD-6000 X-ray diffractometer in Cu Kα-radiation. Additionally, the phase composition and the type of crystal structure of the studied powder was analyzed by X-ray diffractometer MicroMax-007 HF (Rigaku, Japan) in Mo-Kα radiation, λ = 0.71146 Å. The refinement of crystal structure was carried out with Rietveld analysis,⁴⁴ using the FullProf software.⁴⁵ The microstructural characterization of the La₀.₆Ag₀.₂Mn₁.₂O₃ nanopowder was performed using JEOL JEM-2200FS transmission electron microscopy (TEM). High-resolution TEM (HRTEM) with an accelerating voltage of 200 kV was also used to image La₀.₆Ag₀.₂Mn₁.₂O₃ nanoparticles. A sample for the TEM analysis was prepared by placing a drop of diluted suspension of particles in acetone onto a carbon coated copper grid. Particle morphology and particle size were determined by scanning electron microscopy (SEM) on an FEI MAGELLAN 400 Scanning Electron Microscope. Magnetic measurements were carried out on a Quantum Design SQUID MPMS 3 SQUID magnetometer in the temperature range from 2 to 400 K and in magnetic fields up to 70 kOe.

4. Results and discussion

4.1. Structure, phase composition, morphology, and the size of nanoparticles

According to X-ray data (see Fig. 1), the crystal structure of the La₀.₆Ag₀.₂Mn₁.₂O₃ nanopowder is well described in the framework of rhombohedral R3c space group (No. 167). The sample has a small quantity of impurities: Ag (~2%) and La(OH)₃ (~2%). The parameters and volume of perovskite unit cell in the hexagonal setup are equal to a = 5.4969(2) Å, c = 13.297(1) Å and V = 347.96(4) Å³, respectively. The X-ray density of La₀.₆Ag₀.₂Mn₁.₂O₃ with a molar mass of 218.8 g mol⁻¹ and an amount of Z = 6 molar formulas per unit cell is ρₓ = 6.266 g cm⁻³. The preservation of structural single-phase up to 96% with a large amount of 20% super-stoichiometric manganese and its absence in minor phases indicates its complete dissolution in the perovskite structure with completed manganese B-sublattice.

According to the SEM and TEM studies, the La₀.₆Ag₀.₂Mn₁.₂O₃ nanopowder consists of spherical-like nanoparticles with an average particle size of DₓEQ = 65 ± 1 nm (see ESI 2†) and DₓEQ ~ 60 nm (see Fig. 2a), which is in agreement with the XRD, since an average size of the coherent scattering regions is DₓEQ = 62 ± 2 nm (see ESI 1†). HRTEM image of the sample (Fig. 2b) clearly shows the lattice interplanar distance of the La₀.₆Ag₀.₂Mn₁.₂O₃ nanoparticles. The Fast Fourier Transform (FFT) using Gatan Microscopy Suite software was used to measure the interplanar distance (see insert in Fig. 2b).
demonstrates the corresponding lattice plane intensity profile. The interplanar distance of 0.382 nm (012) obtained from FFT is in a good agreement with the XRD data.

The availability of even a slight dispersion in the size \( D \) can lead to the magnetic particles being in both the SD and MD states. The magnetic state of a particle affects the magnetic loss of the nanopowder. Establishment of boundary sizes for the La\(_{0.6}\)Ag\(_{0.2}\)Mn\(_{1.2}\)O\(_3\) nanopowder, when the transition is observed from one magnetic state to another one, is of interest from a practical point of view for hyperthermia. For this purpose, it is necessary to study the magnetic properties of the La\(_{0.6}\)Ag\(_{0.2}\)Mn\(_{1.2}\)O\(_3\) nanopowder in wide temperature and magnetic field ranges.

### 4.2. Magnetic properties of La\(_{0.6}\)Ag\(_{0.2}\)Mn\(_{1.2}\)O\(_3\) nanopowder

The temperature dependences of the \((M/H)_{ZFC}(T)\) and \((M/H)_{FC}(T)\) magnetic susceptibility (see Fig. 3) correspond to a typical manifestation of the magnetic properties of a nanopowder that consists of non-interacting SD FM nanoparticles with randomly oriented uniaxial magnetic anisotropy.\(^42\)\(^-\)\(^45\) The Curie temperature \( T_C \) = 308 K was determined from the temperature dependences of the \(d(M/H)/dT\) derivative (see inset on Fig. 3). The blocking temperature \( T_B \) = 301 K is the maximum of the ZFC curve.\(^46\) For \( T < T_B \), the MNPs are in the blocked state. At \( T > T_B \), the particles go into superparamagnetic (SPM) unblocked state and the ZFC and FC curves should coincide.\(^47\) Usually, the effective anisotropy constant \( K_{\text{eff}} \) is determined using a simple its connection with the temperature \( T_B \):\(^48\)

\[
K_{\text{eff}}V = 25k_BT_B. \tag{5}
\]

From eqn (5), the constant \( K_{\text{eff}} = 7.123 \times 10^3 \) erg cm\(^{-3}\) is calculated for the La\(_{0.6}\)Ag\(_{0.2}\)Mn\(_{1.2}\)O\(_3\) nanopowder with the blocking temperature \( T_B \) = 301 K and the average size of \( D_0 = 65.3 \) nm for spherical particles.

A more detailed analysis of the ZFC/FC curves made it possible to determine the irreversibility temperature \( T_{\text{irr}} \) = 315 K above of which the temperature hysteresis in the magnetization dependences is completely absent. The \( T_B \neq T_{\text{irr}} \) condition confirms the result of the SEM studies because there is size dispersion in the La\(_{0.6}\)Ag\(_{0.2}\)Mn\(_{1.2}\)O\(_3\) nanopowder. In the ideal case for non-interacting MNPs with the same size \( D \), the blocking temperature \( T_B \) and the irreversibility temperature \( T_{\text{irr}} \) should coincide. In real cases, due to the size dispersion of the particles, the temperature is \( T_B < T_{\text{irr}} \). It is associated with particles with a large size \( D \), where the blocking temperature \( T_B \) is higher according to eqn (5). However, a slight difference between the temperatures of \( T_B \) and \( T_{\text{irr}} \) allows concluding that MNPs with almost the same size take part in the formation of the magnetic properties of the La\(_{0.6}\)Ag\(_{0.2}\)Mn\(_{1.2}\)O\(_3\), so the studied nanopowder can be considered to be monodisperse.

Above the temperature \( T_C \), the particles in the La\(_{0.6}\)Ag\(_{0.2}\)Mn\(_{1.2}\)O\(_3\) nanopowder go into the PM state, for which the Curie-Weiss law is fulfilled (see Fig. 4):

\[
\frac{M}{H} = \frac{C}{T-\theta}.
\]

where \( \theta = 307 K \) is the paramagnetic Curie temperature; \( C = N\mu_{\text{eff}}^2/(3k_B) \) is the Curie constant, \( C = 0.015 \) emu K (g Oe)\(^{-1}\); \( N \) is the number of PM manganese ions, \( N = 1 \) for a cubic structure; \( \mu_{\text{eff}} \) is the effective magnetic moment of manganese in Bohr magnetons, \( \mu_{\text{eff}}(\text{Mn}) = 4.61 \mu_B; \mu_B \) is the Bohr magneton. In a wide temperature range from 316 to 400 K, the linear behavior
of the \((H/M)(T)\) dependency with a high accuracy is approximated by the Curie–Weiss law. Below the temperature of appearance of the FM fluctuations at \(T_{C}^{\text{onset}} = 316\) K, the susceptibility deviates from the Curie–Weiss law. This means that in the temperature range from \(T_{C} = 308\) K to \(T_{C}^{\text{onset}} = 316\) K (from \(T_{C} = 34\) °C to \(T_{C}^{\text{onset}} = 43\) °C), the PM and FM phases coexist. The availability of such regions, where FM fluctuations are observed, may cause heating of the La\(_{0.6}\)Ag\(_{0.2}\)Mn\(_{1.2}\)O\(_3\) magnetic powder in AMF to \(T_{C}^{\text{onset}}\).

A very sharp transition to the FM state with a narrow temperature interval \(\Delta T_{C}\) (see Fig. 3) due to the influence of super-stoichiometric Mn is of interest because it satisfies the requirements for magnetic powder with an intelligent local hyperthermia control system. The A- and B-structural positions, valence, and magnetic states of manganese in the nanopowder of non-stoichiometric La\(_{0.6}\)Ag\(_{0.2}\)Mn\(_{1.2}\)O\(_3\) composition are determined and given in (see ESI 3†).

The magnetic hysteresis loops \(M(H)\) in the La\(_{0.6}\)Ag\(_{0.2}\)Mn\(_{1.2}\)O\(_3\) nanopowder were measured in a magnetic field up to \(H = 70\) kOe at temperatures of \(T = 2\), 77, 300, and 400 K (see ESI 3†). The magnetic parameters obtained from hysteresis curves are shown in Table S4 of ESI 3†. With an increase in temperature, the saturation magnetization \(M_{S}\) decreases from \(M_{S} = 69.7\) emu g\(^{-1}\) at \(T = 2\) K to 65.9 emu g\(^{-1}\) at \(T = 77\) K and 34.1 emu g\(^{-1}\) at \(T = 300\) K. At \(T = 400\) K, the dependence \(M(H)\) is linear, as it should be for the PM state. The coercivity \(H_{C}\) and the residual magnetization \(M_{R}\) also decrease from \(H_{C} = 172\) Oe and \(M_{R} = 7.5\) emu g\(^{-1}\) at \(T = 2\) K to \(H_{C} = 109\) Oe and \(M_{R} = 4.9\) emu g\(^{-1}\) at \(T = 77\) K, and to \(H_{C} = 51\) Oe and \(M_{R} = 1.1\) emu g\(^{-1}\) at \(T = 300\) K.

The magnetization isotherms \(M(H)\) of the La\(_{0.6}\)Ag\(_{0.2}\)Mn\(_{1.2}\)O\(_3\) nanopowder are presented in Fig. 5. The magnetization process of the MNPs ensemble can be considered as the magnetization of a uniaxial polycrystalline material, for which the law of approximation to the saturation magnetization \(M_{S}\) is valid in a magnetic field \(H\):\(^{49}\)

\[
M = M_{S}\left(1 - \frac{a}{H} - \frac{b}{H^{2}} - \frac{c}{H^{3}} - \ldots \right) + \chi_{P}H, \tag{6}
\]

where \(a\), \(b\), and \(c\) are constant coefficients, where only coefficient \(b\) is related to the magnetocrystalline anisotropy, and \(\chi_{P}\) is the high field susceptibility. For rare-earth manganites with a cubic crystalline perovskite structure, the coefficient \(b\) is:\(^{30}\)

\[
b = \frac{1}{M_{S}^{2}}\left(\frac{8}{105}K_{1}^{2} + \frac{4}{15}K_{\text{eff}}^{2}\right). \tag{7}
\]

While approximating the isotherm \(M(H)\) for \(T = 2\) K by the dependence (6) (see Fig. 6), the coefficient \(b = 131.38\) Oe\(^2\) was obtained. Using eqn (7) with a saturation magnetization \(M_{S} = 426.8\) emu cm\(^{-3}\) (69.7 emu g\(^{-1}\)), the magnetocrystalline anisotropy constant \(K_{1} = 9.5 \times 10^{3}\) erg cm\(^{-3}\) was obtained.

Using above received parameters of La\(_{0.6}\)Ag\(_{0.2}\)Mn\(_{1.2}\)O\(_3\), for making conclusion about possibility to use its for local hyperthermia, all necessary for that characteristics were calculated (see ESI 4†) and presented here: magnetic hardness parameter \(k = 0.008\), FM exchange length \(l_{ex} = 5.476 \times 10^{-7}\) cm, exchange hardness constant \(A = 3.432 \times 10^{-7}\) erg cm\(^{-1}\), exchange integral \(J_{ex} = 4.63 \times 10^{-15}\) erg and the critical sizes of \(D_{SD} = 39\) nm for the SD state and of \(D_{MD} = 51\) nm for the MD state. The values of the parameter \(k\) satisfy criterion for the soft magnetic particles. The sizes of \(D_{SD}^{\text{MD}}\) and \(D_{MD}^{\text{SD}}\) fully agree with the results of the fundamental work,\(^{52}\) where the \(D_{SD}^{\text{MD}}/D_{MD}^{\text{SD}}\) ratio for the soft magnetic materials should increase with an increase in the parameter \(k\) from 1.2562 at \(k = 0\) to \(\infty\) at \(k = 0.3253\). Comparing the obtained results with conditions of the magnetic state of nanoparticle, it can be concluded that particles with sizes up to 39 nm are in the SD state (7%), sizes from 39 to 51 nm are in the
where $M_\text{s}(T)$ by the power dependence (9), where $T_{\text{FM}}$ and $\beta$ were independent parameters taking $M_\text{S}(0) = 69.7$ emu g$^{-1}$ into account (see Fig. 6). The approximation was conducted in a wide temperature range from 2 K to $T_{C} = 308$ K, regardless of the $T_{\text{irr}} = 315$ K and $T_{\text{irr/set}} = 316$ K temperatures. From the obtained results, the temperature $T_{\text{FM}} = 315$ K coincides with the irreversibility temperature $T_{\text{irr}} = 315$ K. This coincidence means that the heating magnetic particles can be observed above the transition temperature of MNPs to the SPM state at $T_{\text{irr}} = 301$ K up to the $T_{\text{irr}} = 315$ K.

In magnetic hyperthermia, a sinusoidal magnetic field can affect the stimulation of peripheral nerves and cardiac tissue.\textsuperscript{24} In case of choosing the optimal ranges of the frequency $f$ and the amplitude of the magnetic field $H_{\text{max}}$ it is necessary to take into account their boundary limits, above which the effect of AMF on nervous excitement disappears. The upper stimulation threshold is limited by the range from $H_{\text{max}} = 10$ Oe at $f = 100$ kHz to $H_{\text{max}} = 10$ kOe at $f = 10$ Hz.\textsuperscript{25} This means that for therapeutic purposes it is not recommended to use a sinusoidal magnetic field with low values of $f$ and $H_{\text{max}}$.

On the other hand, in order to avoid the harmful effects of electromagnetic fields on the human body, the upper limit of $f \times H$ should not exceed the maximum value of $(f \times H)_{\text{max}}$. In clinical trials, it was found that during hyperthermia for one hour, the subjects did not experience severe discomfort if $(f \times H)_{\text{max}} = 6.3 \times 10^{7}$ Oe s$^{-1} (5 \times 10^{9}$ A m$^{-1}$ s$^{-1})$.\textsuperscript{24} AMF with a high frequency causes nonspecific heating in tissues due to the induced eddy currents, which should be minimized. Therefore, it is advisable to consider the possibility of carrying out the hyperthermia procedure in the range of not too high frequencies $f$ with amplitude AMF, which satisfies the condition $f \times H_{\text{max}} \leq (f \times H)_{\text{max}}$. The results of preclinical studies showed\textsuperscript{26} that there were no adverse effects under AFM ($f = 153$ kHz and $H_{\text{max}} = 700$ Oe) even with continuous magnetic hyperthermia for 20 minutes. The use of magnetic field with $H_{\text{max}} = 1300$ Oe was also acceptable, but keeping heat removal mode with using suitable variations in the duration of electromagnetic pulses.

The heating of SD and monodisperse soft magnetic nanoparticles in the AMF is a result of the hysteresis losses. Fig. 7a shows the temperature changes in the specific loss power, $S_{\text{LP}}(T)$, for the La$_{0.6}$Ag$_{0.2}$Mn$_{1.2}$O$_3$ nanopowder under AMF with $H_{\text{max}} = 700$ Oe and $f = 90$ kHz. At low temperatures, the SLP values were obtained from experimental hysteresis loops (see Table S4) for the quasi-stable hysteresis region using eqn (1) and (2). With an increase in the temperature, the SLP decreases from $S_{\text{LP}} = 46$ W g$^{-1}$ at $T = 2$ K to 19 W g$^{-1}$ at $T = 77$ K, 2 W g$^{-1}$ at $T = 300$ K and 0 W g$^{-1}$ at $T = 316$ K. Such a mechanism for heating the magnetic particles does not consider the relaxation processes of magnetization.

The SLP in the relaxation hysteresis region was determined using eqn (2) and (4). In the case, when the relaxation time $\tau_{\text{R}}$ depends not only on the volume $V$ of the particle, but also on the magnetic anisotropy $K$, the temperature dependence $\tau_{\text{R}}(T)$ has the form:

$$\tau_{\text{R}}(T) = \frac{\tau_{0}}{2} \frac{\exp(KV/k_{B}T)}{\sqrt{KV/k_{B}T}}.$$
For SPM nanoparticles of lanthanum manganites, the characteristic relaxation time $\tau_0$ is $1.7 \times 10^{-12}$ s. Calculating SLP near the magnetic phase transition, it is necessary to consider the parameter $\sigma$ and the magnetic anisotropy $K = K_{\text{eff}}$ for the La$_{0.6}$Ag$_{0.2}$Mn$_{1.2}$O$_3$ nanopowder at $T = 300$ K. The magnetization $M_s(T)$ is a power law dependence $9$ with the temperature $T_{FM} = 315$ K and parameter $\beta = 0.2$. As seen from Fig. 7a, at temperatures $T \leq 250$ K, the specific loss power appears and increases. The SLP increases to a maximum value of 44 W g$^{-1}$ at $T = 310$ K and then reduces dramatically to zero at $T = 315$ K. The resulting SLP for the La$_{0.6}$Ag$_{0.2}$Mn$_{1.2}$O$_3$ nanopowder are in good agreement with the specific absorption rate SAR = 48–54 W g$^{-1}$ for manganite La$_{1-x}$Sr$_x$MnO$_3$ nanoparticles with $0.2 < x < 0.4$. However, lanthanum–strontium manganite is not suitable to the smart material for magnetic hyperthermia, since it does not have a sharp magnetic phase transition at $T_C$ and the Curie temperature is above the range of 42–44 °C of hyperthermia.

A nonmonotonic behavior of the SLP($T$) dependence follows from the relation between the spontaneous magnetization $M_s(T)$ and the relaxation time $\tau_0(T)$ in eqn (4). In the La$_{0.6}$Ag$_{0.2}$Mn$_{1.2}$O$_3$ nanopowder with $\tau_0 = 1.7 \times 10^{-12}$ s, $K_{\text{eff}} = 7.123 \times 10^9$ erg cm$^{-3}$, and $D_0 = 65.3$ nm, the relaxation time decreases from $\tau_0 = 3.243$ s at $T = 250$ K to 0.024 s at $T = 300$ K and 0.007 s at $T = 315$ K. At a frequency $f = 90$ kHz, taking into account the resonance condition $2\pi f_0 \times \tau_0(T) = 1$, it follows that SLP($T$) should take the maximum value at $T = 490$ K. However, the SLP increases inversely with a decrease in $\tau_0(T)$ within the temperature range from 250 to 310 K, since $M_s(T)$ varies slightly. In the range from 310 to 315 K, a sharp decrease in the SLP is due to a sharp drop in $M_s^2$ from 0 (see eqn (4)).

Fig. 7b shows three temperature dependences of SLP($T$) in the relaxation hysteresis region for three pairs of values of $f$ and $H_{\text{max}}$. Each SLP($T$) curve satisfies the condition for the safe influence of AMF on biological subject, i.e. $(f \times H_{\text{max}}) = (f \times H)_{\text{max}} = 6.3 \times 10^7$ Oe s$^{-1}$. In all curves, the maximum of SLP is observed at a temperature $T = 310$ K (37 °C). The maximum temperature is independent of $H_{\text{max}}$ and $f$. With an increase in $H_{\text{max}}$, the maximum of SLP increases from 44 W g$^{-1}$ for $H_{\text{max}} = 700$ Oe and $f = 90$ kHz to 91 W g$^{-1}$ for $H_{\text{max}} = 1000$ Oe and $f = 63$ kHz and up to 153 W g$^{-1}$ for $H_{\text{max}} = 1300$ Oe and $f = 48.3$ kHz. Such an increase in SLP by more than 3 times means the possibility of a significant increase in the heating intensity during hyperthermia. This is due to an increase in the amplitude of AMF when heating occurs in the relaxation hysteresis region. It should be also noted that such an increase in SLP occurs without violating the safe influence of AMF on the vital functions of an organism.

For a complete analysis of the functional properties of the smart magnetic La$_{0.6}$Ag$_{0.2}$Mn$_{1.2}$O$_3$ nanopowder, an unclear question remains regarding whether the such power SLP is sufficient to self-heat of MNP and to heat of the cell structures to the therapeutic range at local hyperthermia. Using equation:

$$\Delta t = \frac{\rho_{\text{NP,cell}} \times V_{\text{NP,cell}} \times C_{\text{NP,cell}} \times (t_2 - t_1)}{\text{SLP} \times m_{\text{NP}}}.$$

($\Delta t$ is the heating time; $\rho_{\text{NP,cell}}$, $V_{\text{NP,cell}}$, and $C_{\text{NP,cell}}$ are the density, volume, and heat capacity of nanoparticle or cell structures, respectively; $t_2$ and $t_1$ are the final and initial temperature, $m_{\text{NP}}$ is the mass of nanoparticles) and assuming that the entire specific thermal power SLP of a spherical nanoparticle with a mass of $8.9 \times 10^{-16}$ g (size $D_0 = 65.3$ nm, density $\rho_s = 6.266$ g cm$^{-3}$) is transferred to cell structures with a size of $500 \times 500 \times 500$ nm (density $\rho_{\text{cell}} = 1.0$ g cm$^{-3}$ and a specific heat capacity $C_{\text{cell}} = 4183$ J (kg K$^{-1}$) for water), then it takes $\Delta t = 79$ s (SLP = $44$ W g$^{-1}$; $H_{\text{max}} = 700$ Oe), 39 s (SLP = $91$ W g$^{-1}$, $H_{\text{max}} = 1000$ Oe), and 23 s (SLP = $153$ W g$^{-1}$, $H_{\text{max}} = 1300$ Oe), to heat one such cell structure at $6$ °C from $t_1 = 36$ to $t_2 = 42$ °C. In this case, self-heating of a magnetic nanoparticle will occur in $\Delta t = 0.09$ s for SLP = $44$ W g$^{-1}$, 0.04 s for SLP = $91$ W g$^{-1}$, and 0.03 s for SLP = $153$ W g$^{-1}$ ($c_{\text{NP}} = 140$ J (mol K$^{-1}$)).
K)$^{-1}$. In less than 1.5 min, the magnetic La$_{0.6}$Ag$_{0.2}$Mn$_{1.2}$O$_3$ nanoparticle with minimum SLP $= 44$ W g$^{-1}$ can increase the temperature of the cell structures, the volume of which is 850 times the volume of the particle itself. It should be also noted that the relaxation mechanism of heating does not cause mechanical damage to cell structures, which can occur during frictional heating as a result of Brownian relaxation. Thus, the synthesized magnetic La$_{0.6}$Ag$_{0.2}$Mn$_{1.2}$O$_3$ nanopowder operating at the intracellular NMR nuclei decreases to the 42$^\circ$C at the intracellular hyperthermia. In the FM state at the intracellular hyperthermia, the formation of the NMR spectrum on $^{55}$Mn nuclei (the gyromagnetic ratio $g_{^{55}Mn} = 10.560$ MHz/T)$^{45}$ occurs under the influence of the hyperfine interaction field $H_{\text{HIF}} = 34-38$ T. The field on $^{139}$La nuclei ($g_{^{139}La} = 6.014$ MHz/T)$^{46}$ has a dipole–dipole character and is in the range $H_{\text{dd}} = 2.3-3.7$ T.$^{65,67}$ In the PM state ($T > T_c$), during MRI studies, the field on the $^{55}$Mn and $^{139}$La NMR nuclei decreases to $\sim 1.5$ T of the tomograph field. Such a variety of magnetic resonance properties of the synthesized La$_{0.6}$Ag$_{0.2}$Mn$_{1.2}$O$_3$ nanopowder operating at the intracellular level additionally opens up great prospects for its use as novel MRI contrast agents for tumor theranostics, which combine the properties of both therapeutic and diagnostic agents.

5. Conclusions

The main characteristics of the magnetic and shape-forming parameters of the smart La$_{0.6}$Ag$_{0.2}$Mn$_{1.2}$O$_3$ material suitable for local (intracellular) hyperthermia have been determined. It has been established that the synthesized La$_{0.6}$Ag$_{0.2}$Mn$_{1.2}$O$_3$ nanopowder consists of spherical-like particles with an average size of 65 nm. The main magnetic properties, such as: magnetic hardness parameter, $k = 0.008$; effective anisotropy constant, $K_{\text{eff}} = 7.123 \times 10^2$ erg cm$^3$; magneto-crystalline anisotropy constant, $K_1 = 9.5 \times 10^3$ erg cm$^3$; anisotropy field, $H_k = 44$ Oe (at $T = 0$); critical size of SD state, $D_{\text{SD}}^c = 39$ nm (at $T = 2$ K); critical size of MD state, $D_{\text{MD}}^c = 51$ nm (at $T = 2$ K); Curie temperature, $T_C = 308$ K; blocking temperature, $T_B = 301$ K; and temperature of appearance of FM fluctuations, $T_{\text{fM}} = 316$ K have been determined for the La$_{0.6}$Ag$_{0.2}$Mn$_{1.2}$O$_3$ nanopowder. These magnetic parameters clearly demonstrate the possibility of using La$_{0.6}$Ag$_{0.2}$Mn$_{1.2}$O$_3$ as a smart magnetic nanomaterial for local (intracellular) hyperthermia. In AMF, the appearance and increase in the SLP near $T_c$ are associated with the influence of the Néel relaxation. Intensive heating of MNPs in the relaxation hysteresis continues up to temperature 42$^\circ$C with a maximum value of SLP at $t = 37$ $^\circ$C. Such thermomagnetic properties allow locally heating cell structures to 42$^\circ$C for a short time, stabilizing this temperature and carrying out magnetic hyperthermia without the risk of overheating and mechanical damage to biological tissue. Obtaining such necessary functional properties has become possible due to the use of the La$_{0.6}$Ag$_{0.2}$Mn$_{1.2}$O$_3$ composition with a super-stoichiometric manganese which demonstrates relaxation hysteresis of magnetization in the temperature range of the magnetic phase transition. Moreover, the presence of $^{55}$Mn and $^{139}$La NMR centers, as well as unique variety and combination of functional properties in the La$_{0.6}$Ag$_{0.2}$Mn$_{1.2}$O$_3$ nanopowder expand the functionality of using this smart material.

Conflicts of interest

There are no conflicts to declare.

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