



Evaluation of electrical properties of poly(NIPA-co-St) composites containing neodymium and yttrium

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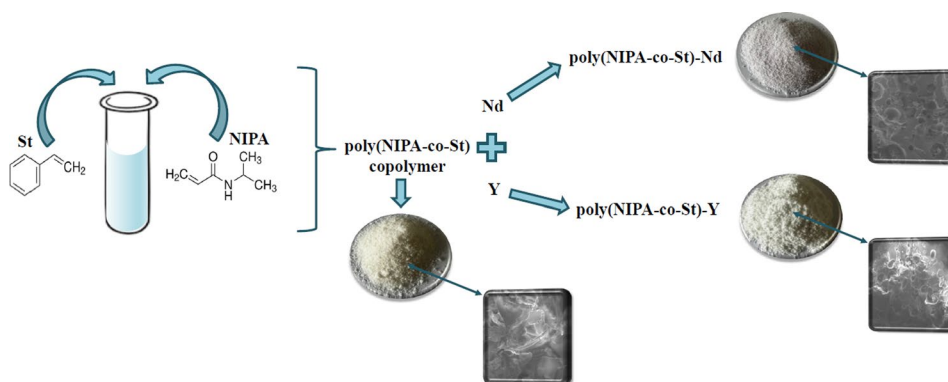
ABSTRACT

In this study, firstly, to obtain neodymium (Nd) and yttrium (Y)-containing composite materials, poly(N-isopropylacrylamide-copolymer-styrene) (poly(NIPA-co-St)) copolymer was synthesized by free radical polymerization method using N-isopropylacrylamide (NIPA) and styrene (St) monomers. Secondly, new composite materials were obtained by adding neodymium and yttrium to this copolymer at different weight ratios (10% and 20%). Structural and morphological characterizations of poly(NIPA-co-St) copolymer, poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y and poly(NIPA-co-St)-20%Y composite materials were carried out. The electrical properties of the copolymer and composite materials were evaluated by considering the frequency dependence of the dielectric constant (ϵ'), dielectric loss (ϵ'') and electrical conductivity (σ_{ac}) properties. At 100 Hz, the ϵ' , ϵ'' , and σ_{ac} values of the copolymer were 5.12, 0.05, and 2.29×10^{-10} S/cm, respectively. With the addition of 10% Nd, the ϵ' , ϵ'' , and σ_{ac} values at 100 Hz were calculated as 6.57, 0.10, and 1.79×10^{-9} S/cm, respectively, while with the addition of 20% Nd, these values were calculated as 8.39, 0.15, and 4.78×10^{-8} S/cm at 100 Hz. With the addition of 10% Y, the ϵ' , ϵ'' , and σ_{ac} values at 100 Hz were calculated as 6.56, 0.053, and 1.81×10^{-9} S/cm, respectively, while with the addition of 20% Y, these values were calculated as 8.57, 0.0058, and 3.70×10^{-8} S/cm at 100 Hz. It can be stated that as the amount of Nd and Y additives to the poly(NIPA-co-St) copolymer increases, the ϵ' , ϵ'' , and σ_{ac} values increase, indicating an improvement in electrical properties with the addition of Nd and Y elements.

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GRAPHICAL ABSTRACT



Introduction

Rare earth elements (REEs) are elements of the lanthanide group, which form a subseries of transition metals in the periodic table. Scandium (Sc) and yttrium (Y) transition metals, which are composed of elements located between lanthanum with atomic number 57 and lutetium with atomic number 71, are included in this group due to their similar chemical properties to lanthanides. These elements are used in many industries such as different engine technologies, energy production sources, digital and imaging devices [1–4]. Rare earth elements can also be added to polymer composite materials to produce polymer–metal composite materials, and their weak dielectric properties can be changed [5–10]. Thus, polymer–metal composites are produced, and these materials are known to be smart and lightweight, possessing both organic and inorganic unit properties. The addition of metals or different fillers allows for the making of polymer composite materials with new functional properties, and the mechanical, optical, thermal, and dielectric versatility of these materials enables their use in many fields such as automotive, aerospace, and electronics [11]. The dielectric properties of polymer composite materials vary depending on factors affecting the material's formation, such as the conductive filler (EuCl_3 , clay, graphene, graphite, metal oxides, silicates, ceramics etc.), its quantity, and the method of preparation. This allows the production of new materials with different mechanical, electrical, optical, thermal, or magnetic properties [12–14]. Any type of functional or structural unit can be incorporated into the polymer matrix using various bonding techniques (physical, chemical

bonding, etc.) [5]. The addition of metal salts to polymers with poor dielectric properties can significantly alter electrical conductivity. Furthermore, the use of ferrites, which have excellent electronic properties and are promising for practical applications, is also preferred in the production of polymer composite materials, and they are known to have a stable structure against environmental factors [15, 16]. Furthermore, it is known that the combination of different compounds with excellent electronic properties (e.g., ferrites) has led to new composite materials that have attracted great technological interest in recent years and are also stable against environmental factors [15–17]. Adding metal salts to composite materials in a second phase can significantly improve their electronic properties [17, 18].

In particular, the addition of metal salts to polymers with poor dielectric properties can significantly alter electrical conductivity of composite materials, making them preferable for use in electrical and electronic fields. These materials are preferred for portable electronics applications due to their properties such as high dielectric constant, low dielectric loss, good mechanical flexibility, chemical resistance, low cost, easy processability, and mechanical flexibility for advanced electrical applications [19–22].

The aim of this study is to investigate the detailed structural and dielectric properties of polymer–metal composite materials obtained by adding neodymium and yttrium polymers, which are rare earth elements, to the polymer material. In this context, it was aimed to (i) synthesize poly(NIPA-co-St) copolymer, (ii) obtain new composite materials by adding neodymium (Nd) and yttrium (Y) elements to this copolymer in different

weight ratios, (iii) evaluate the electrical properties of the copolymer and new composite materials by taking into account the frequency dependence of dielectric constant, dielectric loss and conductivity properties.

Experimental

Materials

N-isopropylacrylamide (NIPA, 99.75%) from Ambeed, styrene (St), 1,4-dioxane (99.8%) and from Sigma-Aldrich, $\text{NdNO}_3 \cdot 6\text{H}_2\text{O}$ (99.9%) from ABCR, $\text{Y}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ (99.9%) from Alfa Aesar, hexane from LiChrosolv were supplied. All chemicals and solvents were analytically pure. Deionized water was used in all experimental studies.

Synthesis of poly(NIPA-co-St) copolymer

For the synthesis of poly(NIPA-co-St) copolymer using NIPA and St monomers, 1 g NIPA was dissolved in 2 mL acetone and 2 mL 1,4-dioxane was added and mixed. Then, 1 g of St was added, mixed, and 0.02 g of azobisisobutyronitrile (AIBN) was added as a reaction initiator, stirred, and after the dissolution was completed, argon gas was passed through the solution for 10 min to remove oxygen. The polymerization process was carried out in a capped test tube, and the reaction was carried out in an oil bath set at approximately 70 °C. The polymerization reaction continued for 24 h, and the thickened polymer was precipitated in hexane and filtered. The polymer, which was kept at room temperature for a while, was dried in an oven at 40 °C for 24 h, and poly(NIPA-co-St) copolymer was obtained.

Preparation of poly(NIPA-co-St)-Nd and poly(NIPA-co-St)-Y composite materials

Poly(NIPA-co-St)-Nd and poly(NIPA-co-St)-Y composites were synthesized using the solution mixing technique. A 0.5 g of each poly(NIPA-co-St) copolymers were dissolved separately in 20 mL dichloromethane. After the dissolution process was completed, 10% and 20% by weight Nd and Y were added to the copolymer solutions and allowed to disperse homogeneously in an ultrasonic water bath for approximately 30 min. The obtained solutions were precipitated in hexane, kept at room temperature for

a while, and then dried in the oven at 40 °C for 24 h, and thus, poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y and poly(NIPA-co-St)-20%Y composites were obtained.

Characterization studies of poly(NIPA-co-St) copolymer, poly(NIPA-co-St)-Nd and poly(NIPA-co-St)-Y composite materials

The structural characterizations of poly(NIPA-co-St) copolymer and poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-co-St)-20%Y composite materials were carried out by Fourier transform infrared spectrophotometer (FTIR, JASCO 6700, Japan) and X-ray diffractometer (XRD, Rigaku miniflex-600), and morphological structure and elemental distributions were carried out by scanning electron microscope and energy-dispersive spectroscopy (SEM-EDS, Hitachi S-3500, Japan).

Dielectric properties of poly(NIPA-co-St) copolymer, poly(NIPA-co-St)-Nd and poly(NIPA-co-St)-Y composite materials

The dielectric properties of poly(NIPA-co-St) copolymer and poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-co-St)-20%Y composite materials were studied as a function of frequency at room temperature using A Novocontrol Technologies (Alpha-AN) impedance analyzer specifications 100 Hz–20 kHz. Dielectric constant (ϵ'), dielectric loss (ϵ''), and a.c conductivities (σ_{ac}) are calculated using Eqs. (1), (2), and (3).

$$\epsilon' = \frac{C_p d}{\epsilon_0 A} \quad (1)$$

$$\epsilon'' = \epsilon' \times D_F \quad (2)$$

$$\sigma = \frac{G d}{A} \quad (3)$$

C: Capacitance of the composites measured from 100 to 20 kHz, D: Thickness, A is the area, ϵ_0 : Permittivity of free space permittivity (8.854×10^{-12} F/m), D_F : Dissipation factor, G: Conductance.

Results and discussion

FTIR analyses of poly(NIPA-co-St) copolymer, poly(NIPA-co-St)-Nd and poly(NIPA-co-St)-Y composite materials

FTIR structural analyses were recorded between 400 and 4000 cm^{-1} on poly(NIPA-co-St) copolymer and poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-co-St)-20%Y composite materials (Fig. 1a and b). When the FTIR spectra were examined, CH bands in the isopropyl group at 2979–2861 cm^{-1} and peaks around 2922 cm^{-1} indicate aliphatic C–H stretching vibrations in the styrene main chain. The peak at 1681 cm^{-1} is associated with the carbonyl group of the amide groups in NIPA [23]. The band at 3080–3020 cm^{-1} represents the aromatic =C–H stretching vibrations of styrene units, the band at 1600 cm^{-1} represents the aromatic C=C stretching vibrations, the ring stretching bands at 1500 cm^{-1} and 1450 cm^{-1} , the two bands at 760 cm^{-1} and 700 cm^{-1} represent the characteristic peaks of the =C–H out-of-plane bending vibrations in the aromatic ring. As seen in the spectra, the FTIR spectra of the poly(NIPA-co-St) copolymer, Nd- and Y-containing composites are basically the same. This indicates that there was a physical interaction between the copolymer and Nd and Y.

SEM-EDS analyses of poly(NIPA-co-St) copolymer, poly(NIPA-co-St)-Nd and poly(NIPA-co-St)-Y composite materials

The surface morphologies of poly(NIPA-co-St) copolymer and poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-co-St)-20%Y composite materials were imaged by SEM, and these images are presented in Fig. 2. According to the SEM images, it was observed that as the amount of Nd and Y added separately to the poly(NIPA-co-St) copolymer increased, the elements accumulated on the surface, and the surfaces of the composite materials became rougher compared to the copolymer. According to the EDS analysis results presented in Fig. 2, the element weight ratios were determined as 7.9% Nd for poly(NIPA-co-St)-10%Nd composite material, 16% Nd for poly(NIPA-co-St)-20%Nd composite material, 0.8% Y for poly(NIPA-co-St)-10%Y composite material, 1.4% Y for poly(NIPA-co-St)-20%Y composite material. According to these results, it was determined that as the amount of Nd increases, the amount of Nd on the surface of the composite material increases proportionally and a homogeneous distribution occurs, and the mapping images showing the distribution of elements in the poly(NIPA-co-St)-20%Nd composite material are given in Fig. 2. As the amount of Y increases, the amount of Y on the surface of the composite material decreases depending on the added amount, and this

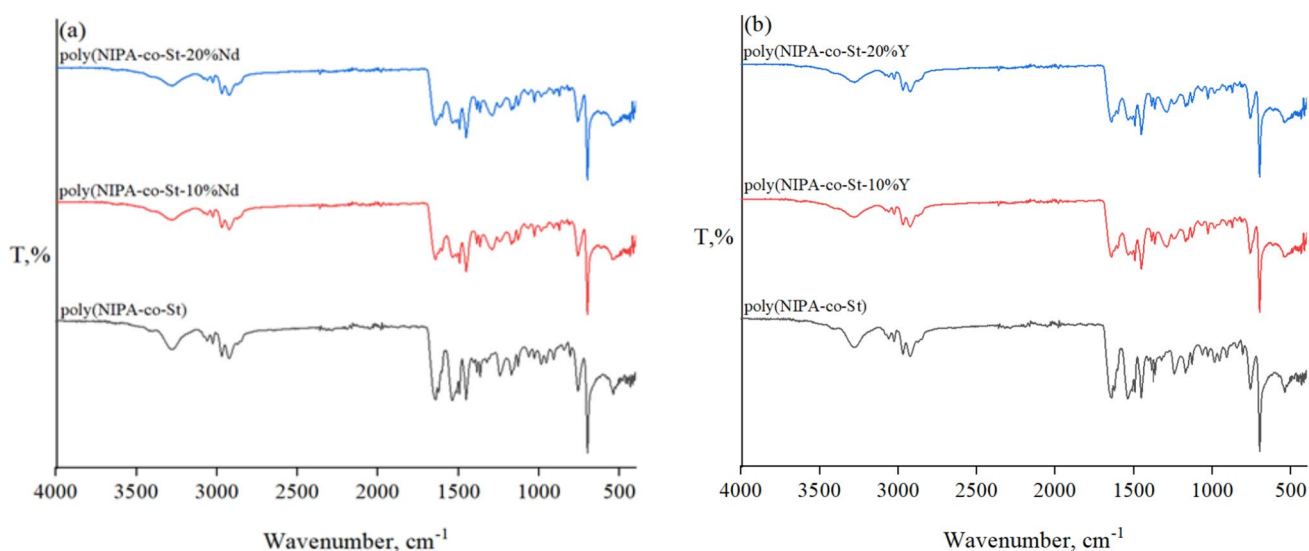


Figure 1 FTIR spectrums of poly(NIPA-co-St) copolymer, poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-co-St)-20%Y composite materials.

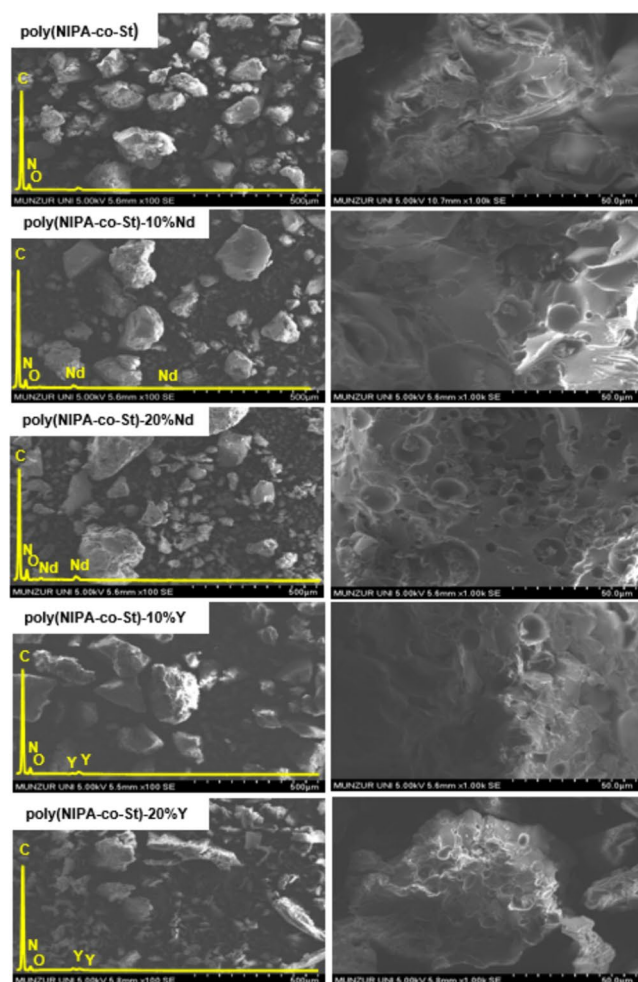


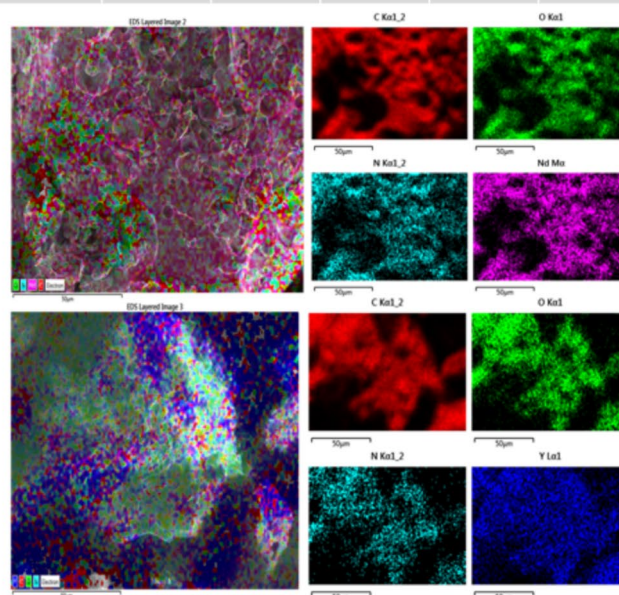
Figure 2 SEM images, EDS spectrums, and elemental distributions of poly(NIPA-co-St) copolymer, poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-

situation is seen in the mapping images showing the distribution of elements in the poly(NIPA-co-St)-20%Y composite material (Fig. 2).

XRD analyses of poly(NIPA-co-St) copolymer, poly(NIPA-co-St)-Nd and poly(NIPA-co-St)-Y composite materials

The crystallinity properties of poly(NIPA-co-St) copolymer and poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-co-St)-20%Y composite materials were measured by XRD, and these results are presented in Fig. 3. A new peak was observed around 43.5° in the XRD graph of poly(NIPA-co-St)-10%Nd and poly(NIPA-co-St)-20%Nd composites obtained by adding different

	poly(NIPA-co-St)	poly(NIPA-co-St)-10%Nd	poly(NIPA-co-St)-20%Nd	poly(NIPA-co-St)-10%Y	poly(NIPA-co-St)-20%Y
Element	Wt%	Wt%	Wt%	Wt%	Wt%
C	85.8	77.6	69.3	84.5	89.0
O	11.5	10.9	11.2	14.0	9.6
N	2.7	3.6	3.5	0.8	0.0
Nd	-	7.9	16	-	-
Y	-	-	-	0.8	1.4



co-St)-20%Y composite materials and EDS mapping images of poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-20%Y composite materials.

amounts of Nd to poly(NIPA-co-St) copolymer. Although the peak intensity of poly(NIPA-co-St) copolymer was high, a decrease in the peak intensities was observed as the amount of Nd increased. In addition, the FWHM value of the poly(NIPA-co-St) copolymer was 43.5° , while FWHM value of poly(NIPA-co-St)-10%Nd composite was 11.9° , and the FWHM value of poly(NIPA-co-St)-20%Nd composite was 8.4° . It can be said that with the addition of neodymium, the FWHM value starts to decrease, crystallinity slightly increases, and the crystal structure becomes more ordered. This indicates grain growth or improved crystallinity. No significant peak change was observed in the XRD graph of poly(NIPA-co-St)-10%Y and poly(NIPA-co-St)-20Y composites obtained by adding different amounts of Y to the

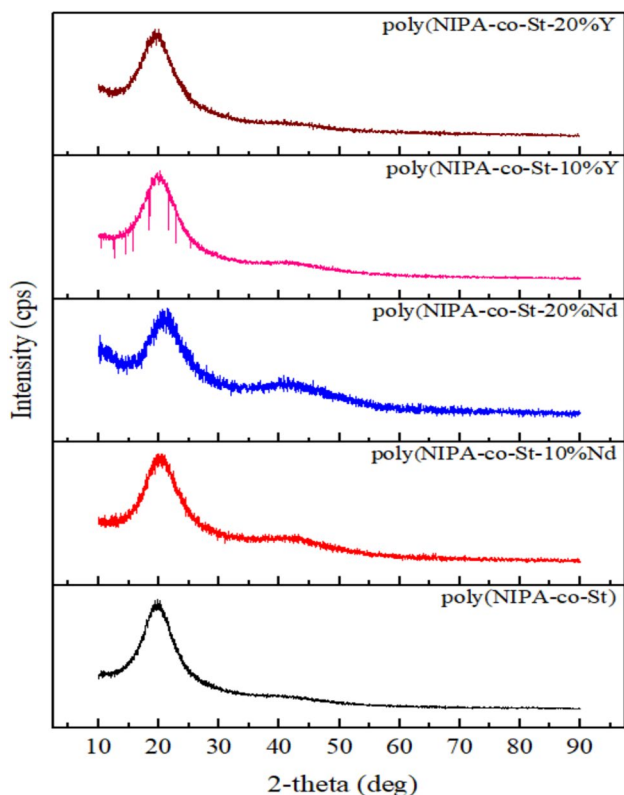


Figure 3 XRD analyzes of poly(NIPA-co-St) copolymer, poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-co-St)-20%Y composite materials.

poly(NIPA-co-St) copolymer. However, although the peak density of the poly(NIPA-co-St) copolymer was high, a decrease in peak density was observed as the amount of Y increased, and therefore, it can be said that its crystallinity was low. Furthermore, a slight shift in 2-theta values after adding both elements may indicate a limited change in crystal lattice parameters. Also, the changes in the average crystallite size and crystallite size distribution of the obtained samples with annealing temperature were not investigated. However, it is known that crystallite size affects the electrochemical properties [24, 25].

Electrical properties of poly(NIPA-co-St) copolymer, poly(NIPA-co-St)-Nd and poly(NIPA-co-St)-Y composite materials

The frequency-dependent dielectric constant (ϵ') graphs of poly(NIPA-co-St) copolymer and poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-co-St)-20%Y composite materials are given in Fig. 4a and b. As seen in Fig. 4a, the ϵ' values of poly(NIPA-co-St) copolymer and Nd-containing composites decreased with the increase in frequency from 100 Hz to 10 kHz and remained constant at higher frequencies. The polarization formed in a regularly changing electric field causes the dielectric constant of the polymers to change. The ϵ' values are higher at low frequencies due to electronic, atomic, ionic and interfacial polarization

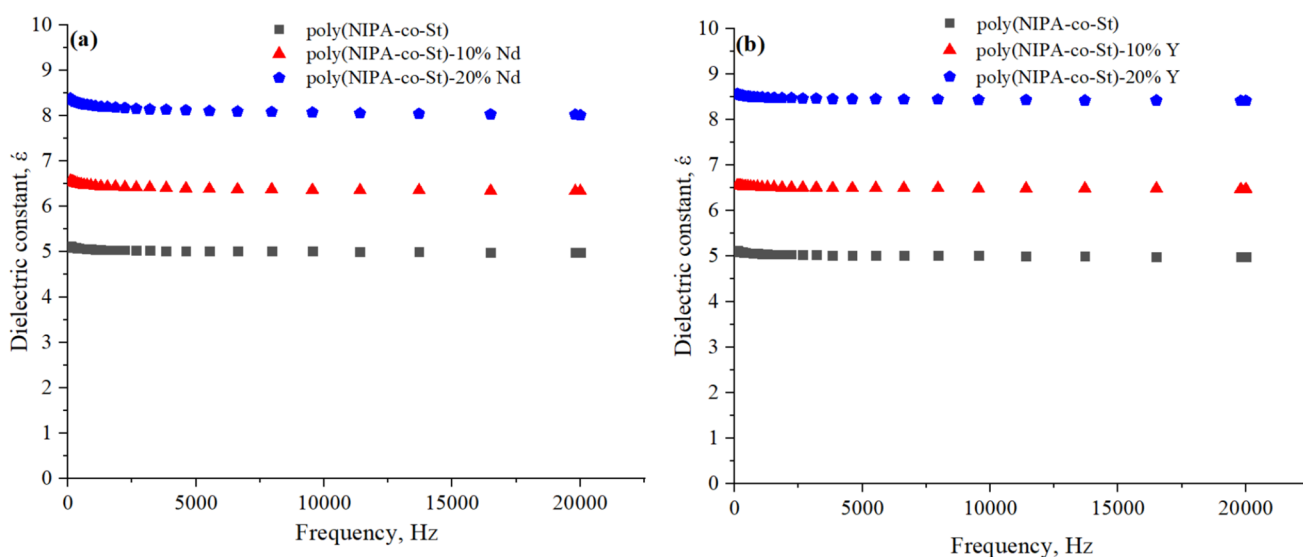


Figure 4 Frequency dependence of dielectric constant of poly(NIPA-co-St) copolymer, poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-co-St)-20%Y composite materials.

and decreased as the frequency increased [26]. At high frequencies, only electrical polarization occurs, so the number of dipoles is less and ϵ is small [23]. The dielectric constant for poly(NIPA-co-St) copolymer is 5.12 at 100 Hz, while it is 5.05 at 10 kHz and 4.99 at 20 kHz, respectively. It was also found that the ϵ value of the copolymer increased with the increase of the Nd adding amount. The 20 wt% Nd loading increased the ϵ values by approximately 1.7 times compared to the poly(NIPA-co-St) copolymer without Nd at a fixed frequency. This increase in ϵ can be attributed to the interfacial polarization that occurs at the interface between Nd particles and polymer molecules [27, 28]. Well-dispersed fillers in the polymer provide higher ϵ values. When the results obtained with the composite materials prepared by adding Y to Fig. 4b are examined, the dielectric constant for each sample decreased gradually with increasing frequency. This phenomenon can be explained by the frequency dependence of different polarization mechanisms in the samples when the electric field is applied [29, 30]. The dielectric constant for all samples is because of dipole orientation and interfacial polarization. At high frequencies, the dipole mobility is restricted since the frequency of the applied electric field exceeds the relaxation frequency. In addition, interfacial polarization weakens, causing the dielectric constant decrease of electricity. It is also observed in Fig. 4b that the dielectric constant remains constant after 5 kHz. Because the mobility of free carriers is assumed to be constant along with the polymer at these frequencies. In addition, a gradual increase in the ϵ value was observed with the Y content in the composites. The dielectric constant of the poly(NIPA-co-St)-20%Y composite reached 8.57 at 100 Hz. This value is approximately 1.7 times higher than the ϵ value of the poly(NIPA-co-St) copolymer. As can be seen, it was possible to achieve high dielectric constants even when the weight ratios of fillers in the polymer were low. At 10 kHz, the ϵ of the poly(NIPA-co-St)-10%Y composite was 6.52, while the ϵ of the poly(NIPA-co-St)-20%Y composite was 8.50. The advantage of the low filler content is that the polymer retains its flexibility for practical applications. The variation of the dielectric constant (ϵ) of didymium heptamolybdate was carried in the temperature range (30–150 °C) under the application of applied a.c. field in the frequency range (10^2 – 10^7 Hz). At the initial temperature (room temperature 30 °C), the ϵ value increases at low frequencies, decreases as the frequency increases, and remains constant over time

[31]. The influence of RE-oxide dopants on the electrical, dielectric, and optical properties of polyvinyl alcohol (PVA) films doped with rare-earth oxides- Y_2O_3 , Pr_6O_{11} , and Ta_2O_5 . The PVA- Y_2O_3 , PVA- Ta_2O_5 , and PVA- Pr_6O_{11} films with a concentration of 1.5% of the oxides were prepared by the casting method. The results reveal that increasing RE-oxide dopants enhances conductivity, dielectric relaxation, and modulus properties by reducing oxygen vacancies and strengthening metal–oxygen bonds [32].

The dielectric loss factor variation with frequency for poly(NIPA-co-St) copolymer and poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-co-St)-20%Y composite materials is given in Fig. 5a and Fig. 5b. The dielectric loss (ϵ'') values for the composites prepared with poly(NIPA-co-St) and Nd decreased with increasing frequency. This can be attributed to the free charge movement within the materials at low frequencies. It is observed that ϵ'' values remain constant at high frequencies. The dielectric loss of poly(NIPA-co-St) copolymer was determined as 0.05 at 100 Hz and 0.04 at 10 kHz. Like the dielectric constant, Nd-containing composites increased the ϵ'' values. When the change of dielectric loss factor of the composites prepared by adding Y to the copolymer is examined with frequency in Fig. 5b, it is seen that ϵ'' values decrease with increasing frequency up to 6 kHz and are not completely dependent on frequency at high frequencies for all the composites examined. The higher ϵ'' at low frequency is due to the free charge movement within the polymer [33]. In addition, the high ϵ'' values at low frequencies are due to the presence of sufficient time for the dipoles to interact with the applied electric fields before changing. At higher frequencies, ϵ'' decreases due to the short time available to them [34]. In addition, ϵ'' increased with the increase in the amount of filler in the composite, which is attributed to the interfacial polarization mechanisms in a heterogeneous system. At a frequency of 1000 Hz, the dielectric loss for poly(NIPA-co-St) polymer was determined as 0.04, for poly(NIPA-co-St)-10%Y composite material as 0.042 and for poly(NIPA-co-St)-20%Y composite material as 0.045. These values show that the Y additive has a significant effect on the dielectric properties of the composites. Pure and 2% Y and Gd-doped NiO nanoparticles, capped with PVA, were successfully prepared by coprecipitation method. The dielectric constant increased for higher dopant ionic radius and valency. This was accompanied by the increase

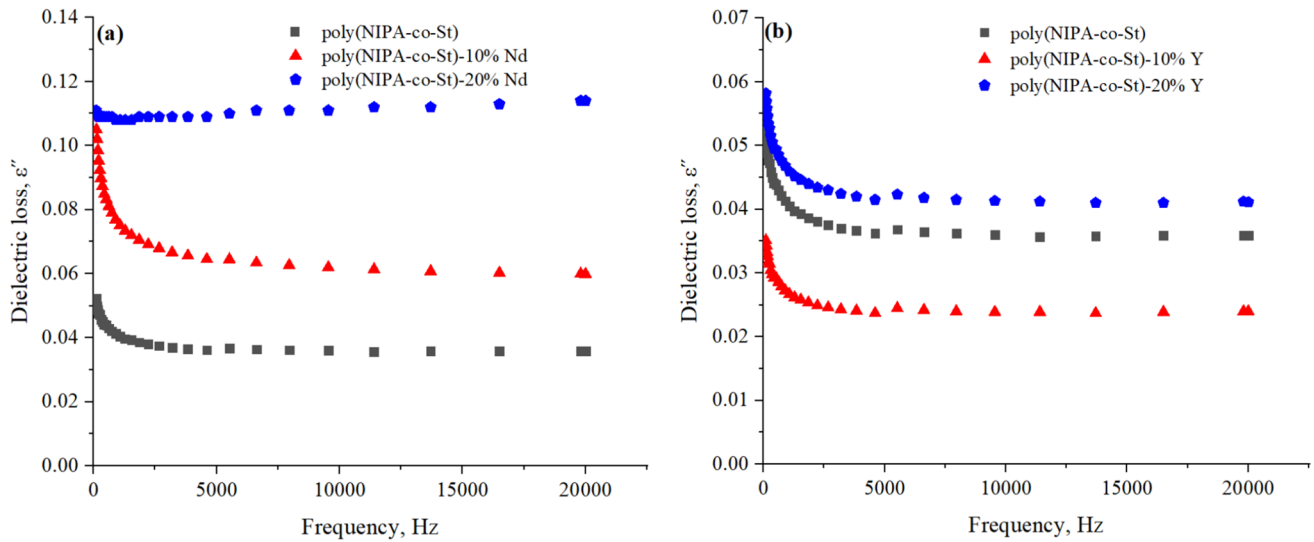


Figure 5 Frequency dependence of dielectric loss of poly(NIPA-co-St) copolymer, poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-co-St)-20%Y composite materials.

in dielectric loss, because of the larger polarization in the doped samples. It was found that doping by Y^{3+} and Gd^{3+} increases the ac conductivity of NiO nanoparticles [35]. A study discussed the loss factor of composite materials containing a low-density polyethylene (LDPE) matrix and neodymium (Nd) filler, measured at frequencies between 1 mHz and 1 MHz and temperatures between 30 and 80 °C. The loss factor varies depending on the frequency of the electric field, temperature, and filler content. For specific frequency

values, the loss factor shows increasing maximum values as temperature and filler content increase [36].

The electrical conductivity (σ_{ac}) of poly(NIPA-co-St) copolymer and poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-co-St)-20%Y composite materials was investigated as a function of frequency and is presented in Fig. 6a and b. In the measurements carried out at room temperature, the electrical conductivity increased with increasing frequency for poly(NIPA-co-St) copolymer

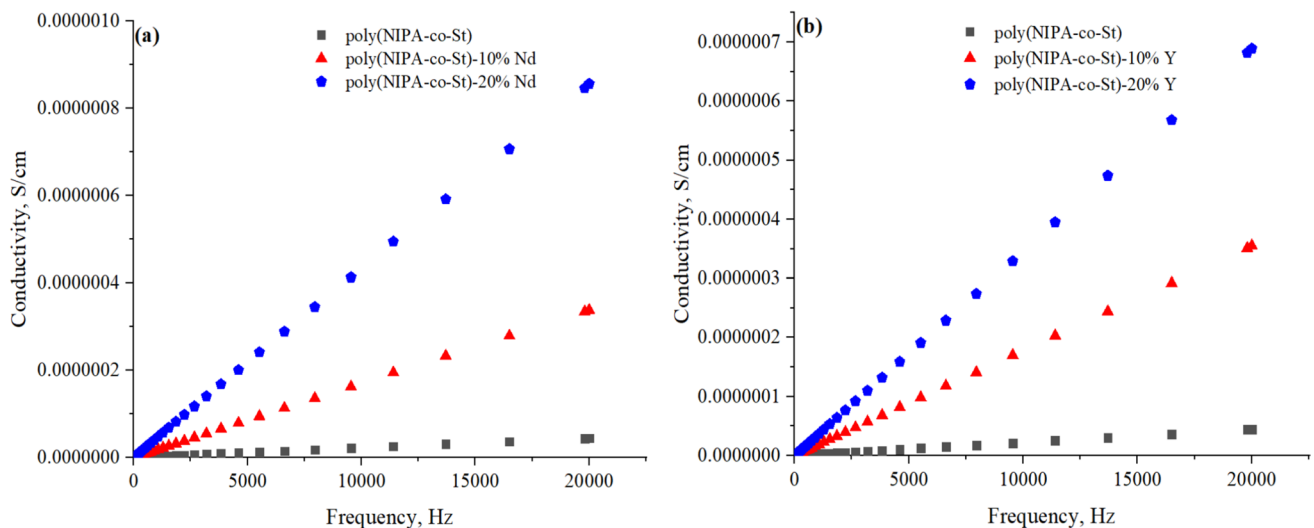


Figure 6 Frequency dependence of electrical conductivity of poly(NIPA-co-St) copolymer, poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-co-St)-20%Y composite materials.

and poly(NIPA-co-St)-10%Nd and poly(NIPA-co-St)-20%Nd composites. The conductivity values for poly(NIPA-co-St) copolymer were found to be 2.29×10^{-10} S/cm at 100 Hz and 2.41×10^{-9} S/cm at 10 kHz. This increase in conductivity may be due to the different behaviors of charge carriers at low and high frequencies. At low frequencies, the transition of more than one charge carrier from one segment to another is provided by tunneling and a small amount of electricity is provided. At higher frequencies, more conductivity is observed due to the tunneling of a greater number of charge carriers [14]. Well-dispersed Nd molecules in the polymer gave the polymer higher conductivity. It was found that the conductivity of poly(NIPA-co-St)-Nd composites was higher in those containing higher Nd by weight. The conductivity value for poly(NIPA-co-St) copolymer at 1000 Hz at room temperature was determined as 2.41×10^{-9} S/cm, for poly(NIPA-co-St)-10%Nd composite material as 1.86×10^{-8} S/cm and for poly(NIPA-co-St)-20%Nd composite material as 4.78×10^{-8} S/cm. This increase can be caused by the good interface polarization that increases the electronic and dipole polarization between poly(NIPA-co-St) and Nd molecules [14]. When the electrical conductivity of Y-containing composite materials is evaluated as a function of frequency in Fig. 6b, it is seen that the electrical conductivity increases linearly for all samples with increasing frequency. The conductivity value increased to 2.29×10^{-10} S/cm at 100 Hz, 2.41×10^{-9} S/cm at 1000 Hz and 4.44×10^{-8} S/cm at 20 kHz for poly(NIPA-co-St) copolymer. At lower frequencies, the conductivity is lower due to the interfacial impedance or polarization of space charge. In addition, increasing Y particles in the composite increased the conductivity of the composites. At a frequency of 100 Hz, when the Y content was increased from 10 to 20%, the electrical conductivity of poly(NIPA-co-St)-10%Y and

poly(NIPA-co-St)-20%Y composites increased from 1.81×10^{-9} S/cm to 3.47×10^{-9} S/cm. This increase in conductivity even at low Y content is attributed to the enhanced interfacial polarization or Maxwell–Wagner–Sillars effect [37, 38]. This effect occurs on heterogeneous surfaces consisting of phases with different conductivities due to charge accumulation at the interfaces. When the yttrium content is low, the metal particles are well separated without any interaction between them. Since the yttrium particles are well separated, no bonding occurs between them under the applied electric field and hence the probability of electrons jumping to neighboring particles will be very low [37]. As the yttrium content increases, the number of particles per unit volume and the interfacial area increase while the inter-particle distance (IPD) decreases. This increases the average polarization associated with the particles and the coupling between adjacent grains and contributes more to the conductivity of the composites [37, 39]. In summary, electrical properties of poly(NIPA-co-St) copolymer, poly(NIPA-co-St)-10% Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-co-St)-20%Y composite materials at room temperature are given in Table 1.

Frequency and temperature-dependent conductivity of Tb3+ -doped PVA thin films with and without Cu-nanoparticles have been measured in the frequency range 20 Hz–1 MHz and in the temperature range 318–338 K (well below its melting temperature). The real part of the conductivity spectra has been explained in terms of power law. The electrical properties of the thin films show a decrease in dc conductivity on incorporation of the Cu-nanoparticles [40]. Dielectric constant (ϵ) and conductivity (σ) performance of composites preparing maleic anhydride (MA) and styrene (St) polymer with various amounts of cadmium sulfide (CdS) were investigated. From the analysis results, it was seen that

Table 1 Electrical properties of poly(NIPA-co-St) copolymer, poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%Y, poly(NIPA-co-St)-20%Y composites at room temperature

Copolymer and composites	Dielectric constant (ϵ) 100 Hz	Dielectric constant (ϵ) 10 kHz	Dielectric loss (ϵ'') 100 Hz	Dielectric loss (ϵ'') 10 kHz	Conductivity (σ_{ac}) 100 Hz	Conductivity (σ_{ac}) 10 kHz
Poly(NIPA-co-St)	5.12	5.05	0.05	0.04	2.29×10^{-10}	2.41×10^{-9}
Poly(NIPA-co-St)-10%Nd	6.57	6.46	0.10	0.07	1.79×10^{-9}	1.86×10^{-8}
Poly(NIPA-co-St)-20%Nd	8.39	8.22	0.15	0.11	4.62×10^{-9}	4.78×10^{-8}
Poly(NIPA-co-St)-10%Y	6.56	6.52	0.053	0.042	1.81×10^{-9}	1.92×10^{-8}
Poly(NIPA-co-St)-20%Y	8.57	8.50	0.058	0.045	3.47×10^{-9}	3.70×10^{-8}

high values of dielectric constant and conductivity are strongly related to frequency and CdS amount and increase as the doping amount increases [41].

The oxygen stoichiometry of the prepared composite samples and how it affects their electrical properties have not been investigated. However, stoichiometry is, particularly, important for metal and alloy composite samples. Deviation from stoichiometry and the appearance of oxygen anions can lead to a change in the charge state of cations [24].

Conclusions

- Poly(NIPA-co-St) copolymer was synthesized, and poly(NIPA-co-St)-Nd and poly(NIPA-co-St)-Y were synthesized by adding neodymium (Nd) and yttrium (Y) elements in different weight ratios to this copolymer.
- The copolymer and composite materials containing Nd and Y were characterized. It was determined that copolymer and Nd, Y-containing composite materials were successfully obtained.
- Electrical properties of the copolymer and composite materials containing Nd and Y were examined and evaluated.
- Dielectric properties of poly(NIPA-co-St)-10%Nd, poly(NIPA-co-St)-20%Nd, poly(NIPA-co-St)-10%, poly(NIPA-co-St)-20Y% composite materials dielectric constants, dielectric losses and electrical conductivities were found to be higher than poly(NIPA-co-St) copolymer at varying frequencies.
- It can be said that there is an improvement in electrical properties by adding Nd and Y to poly(NIPA-co-St) copolymer.
- The resulting composite materials can be used in many different areas such as electronic parts, sensors, conductive coatings and capacitors that require electrical conductivity.

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Author contributions

Ebru Cetinkaya involved in investigation, methodology, writing—original draft; Nagihan Karaaslan Ayhan did conceptualization, methodology, investigation, visualization, formal analysis, writing—original draft, writing—review and editing, supervision.; Gulben Torgut contributed in conceptualization, methodology, investigation, formal analysis, writing—original draft.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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