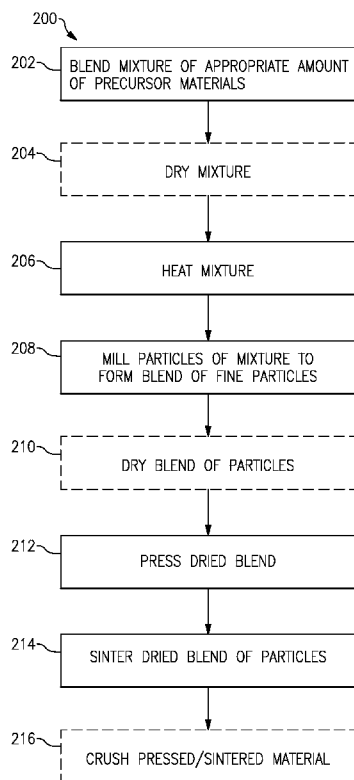




- (51) **International Patent Classification:**
H01F 1/34 (2006.01) **H01Q 7/08** (2006.01)
C04B 35/26 (2006.01)
- (21) **International Application Number:**
PCT/US2012/022241
- (22) **International Filing Date:**
23 January 2012 (23.01.2012)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**
61/435,608 24 January 2011 (24.01.2011) US
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- (81) **Designated States (unless otherwise indicated, for every
kind of national protection available):** AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ,
CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO,
DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN,
HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR,
KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME,
MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,
OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD,
SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR,
TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.
- (84) **Designated States (unless otherwise indicated, for every
kind of regional protection available):** ARIPO (BW, GH,
GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ,
UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU,
TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE,
DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU,
LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,

[Continued on next page]

(54) **Title:** SPECIALTY MATERIALS PROCESSING TECHNIQUES FOR ENHANCED RESONANT FREQUENCY HEXA-
FERRITE MATERIALS FOR ANTENNA APPLICATIONS AND OTHER ELECTRONIC DEVICES

**FIG. 7**

(57) **Abstract:** Processing techniques for forming a textured hexagonal ferrite materials such as Z-phase barium cobalt ferrite $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ (Co_2Z) to enhance the resonant frequency and other magnetic properties of the material for high frequency applications are provided. The processing techniques include magnetic texturing by using fine grain particles and sintering the material at a lower temperature than conventional firing temperatures to inhibit reduction of iron. The processing techniques also may include aligning M-phase ($\text{BaFe}_{12}\text{O}_{19}$ uniaxial magnetization) with non-magnetic additives in a static magnetic field and reacting with BaO source and CoO to form Z-phase ($\text{Ba}_3\text{Me}_2\text{Fe}_{24}\text{O}_{42}$). In some implementations, processing techniques includes aligning Co_2Z phase (planar magnetization) with magnetic texturing occurring in a rotating magnetic field.



SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG). **Published:**

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

**SPECIALTY MATERIALS PROCESSING TECHNIQUES FOR ENHANCED
RESONANT FREQUENCY HEXAFERRITE MATERIALS FOR ANTENNA
APPLICATIONS AND OTHER ELECTRONIC DEVICES**

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority under 35 U.S.C. §119(e) of U.S. Provisional Application No. 61/435,608 filed on January 24, 2011, which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] Embodiments of the invention relate to methods of preparing compositions and materials useful in electronic applications, and in particular, useful in radio frequency (RF) electronics.

Description of the Related Art

[0003] Magneto-dielectric materials are particularly useful in RF devices such as antennas, transformers, inductors, and circulators. Recent advances in magneto-dielectric materials are driven in part by the need to miniaturize high frequency antennas while maintaining desirable bandwidth, impedance, and low dielectric loss. It is also desirable to increase the upper frequency limit of an antenna, which is largely determined by the resonant frequency of the material used.

[0004] Hexagonal ferrites such as Z-phase barium cobalt ferrite ($\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$), commonly abbreviated as Co_2Z , are magneto-dielectric materials often used in high frequency antennas and other RF devices. To improve the performance characteristics of Co_2Z and other hexagonal ferrites, prior art methods are largely focused on substituting certain chemical elements in Co_2Z with others. For example, one such method involves doping Co_2Z with small amounts of an alkali metal such as potassium (K), sodium (Na), or rubidium (Rb) to improve the magnetic permeability of the material at high frequencies, which in turn increases the useable frequency range. However, these chemical substitution

solutions are met with moderate success. As such, there is a continuing need to improve the material properties and performance characteristics of magneto-dielectric materials such as Co_2Z for RF applications.

SUMMARY OF THE INVENTION

[0005] The compositions, materials, methods of preparation of this disclosure each have several aspects, no single one of which is solely responsible for its desirable attributes. Without limiting the scope of this invention, its more prominent features will now be discussed briefly.

[0006] Any terms not directly defined herein shall be understood to have all of the meanings commonly associated with them as understood within the art. Certain terms are discussed below, or elsewhere in the specification, to provide additional guidance to the practitioner in describing the compositions, methods, systems, and the like of various embodiments, and how to make or use them. It will be appreciated that the same thing may be said in more than one way. Consequently, alternative language and synonyms may be used for any one or more of the terms discussed herein. No significance is to be placed upon whether or not a term is elaborated or discussed herein. Some synonyms or substitutable methods, materials and the like are provided. Recital of one or a few synonyms or equivalents does not exclude use of other synonyms or equivalents, unless it is explicitly stated. Use of examples in the specification, including examples of terms, is for illustrative purposes only and does not limit the scope and meaning of the embodiments herein.

[0007] Certain embodiments of the invention provide a method of increasing the resonant frequency of hexagonal ferrite materials. In one embodiment, the method includes forming a fine grain hexagonal ferrite powder in a desired phase and firing the hexagonal powder at a low temperature, preferably lower than standard sintering temperatures for the particular material. In some embodiments, the method further includes compacting the hexagonal ferrite powder before firing. In one implementation, the hexagonal powder is fired at a temperature between about 1100° C to 1250° C. In another implementation, the hexagonal ferrite powder has an average particle size of less than 1 micron, preferably between about 300 nm – 600 nm. In yet another implementation, the hexagonal ferrite powder has a surface area of greater than about 6 m²/g, preferably greater than about 15

m²/g. The resulting material is preferably a fine grained hexagonal ferrite material having a density in the range of about 70%-100% of the theoretical density. The processing techniques cause the hexagonal ferrite material to have reduced magnetorestriction, which increases the resonant frequency of the material and, in turn, results in higher frequency values for antenna applications.

[0008] The hexagonal ferrite materials can include Z type hexagonal ferrites such as $M^I_3M^{II}_2Fe_{24}O_{41}$, Y type hexagonal ferrites such as $M^I_2M^{II}_2Fe_{12}O_{22}$, W type hexagonal ferrites such as $M^IM^{II}_2Fe_{16}O_{27}$, U type hexagonal ferrites such as $M^I_4M^{II}_2Fe_{36}O_{60}$, X type hexagonal ferrites such as $M^I_2M^{II}_2Fe_{28}O_{46}$, and M type hexagonal ferrites such as $M^I_2Fe_{12-2x}M^{II}_xM^{III}_xO_{19}$, wherein M^I is barium (Ba) or strontium (Sr), and M^{II} is a divalent metal such as cobalt (Co), zinc (Zn), nickel (Ni), magnesium (Mg), Manganese (Mn), or copper (Cu), M^{III} is a tetravalent metal such as titanium (Ti), zirconium (Zr), tin (Sn), germanium (Ge), silicon (Si), cerium (Ce), praseodymium (Pr), or hafnium (Hf).

[0009] In another embodiment, a method of increasing the permeability of hexagonal ferrite by magnetic texturing is provided. The method includes aligning M-phase hexagonal ferrite with non-magnetic additives in a static magnetic field and sintering the aligned M-phase hexagonal ferrite with barium oxide and cobalt oxide to form a Z-phase hexagonal ferrite. Preferably, the sintering temperature is lower than 1250°C, or lower than 1200°C, or lower than 1150°C, or lower than 1100°C, or lower than 1050°C, or lower than 1000°C. In one implementation, the M-phase hexagonal ferrite includes $M^I_2Fe_{12-2x}M^{II}_xM^{III}_xO_{19}$, where M^I is selected from the group consisting of barium (Ba) and strontium (Sr), where M^{II} is selected from the group consisting of cobalt (Co), zinc (Zn), nickel (Ni), magnesium (Mg), manganese (Mn), and copper (Cu), and where M^{III} is selected from the group consisting of titanium (Ti), zirconium (Zr), tin (Sn), germanium (Ge), silicon (Si), cerium (Ce), praseodymium (Pr), and hafnium (Hf). In another implementation, the Z-phase hexagonal ferrite includes $M^I_3M^{II}_2Fe_{24}O_{41}$ where M^I is selected from the group consisting of barium (Ba) and strontium (Sr), where M^{II} is selected from the group consisting of cobalt (Co), zinc (Zn), nickel (Ni), magnesium (Mg), manganese (Mn), and copper (Cu).

[0010] Advantageously, the preferred embodiments of the invention provide a method to produce fine grain hexagonal ferrite materials having reduced magnetorestriction and increased resonant frequency without modifying the chemical composition of the

hexagonal ferrite. However, in some embodiments, intergrowths between different phases of materials can apply. Small amounts of dopants such as potassium (K), sodium (Na), rubidium (Rb), or calcium (Ca) can also be added to the hexagonal ferrite further modify the properties.

[0011] Materials formed in accordance with preferred embodiments of the present invention have applications in electronic devices. The enhanced resonant frequency Co_2Z formed in accordance with certain embodiments described herein can be incorporated into numerous types of RF devices including antennas, transformers, inductors, and circulators.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] FIGURE 1 illustrates the crystal structure of a magnetoplumbite cell with the chemical structure $\text{BaFe}_{12}\text{O}_{19}$.

[0013] FIGURE 2 illustrates the relationship between permeability and frequency, showing the effect of spin rotation relaxation at higher frequencies.

[0014] FIGURE 3 illustrates real permeability versus magnetic Q at 700 MHz and at 400MHz of a Co_2Z material formed using a method of the preferred embodiment.

[0015] FIGURE 4 illustrates permeability versus magnetic Q of a Co_2Z material formed using a method of the preferred embodiment.

[0016] FIGURE 5 schematically illustrates that rotational stiffness varies with direction in Co_2Z wherein the θ direction represents high stiffness.

[0017] FIGURE 6 schematically illustrates planar hexagonal anisotropy prior to aligning the material in a rotating magnetic field.

[0018] FIGURE 7 is a flow chart illustrating a method of forming a hexagonal ferrite material according to one preferred embodiment.

[0019] FIGURE 8 is a flow chart illustrating a method of forming a hexagonal ferrite material according to another preferred embodiment.

[0020] FIGURE 9 illustrates the microstructures of Co_2Z of one embodiment at 500X magnification.

[0021] FIGURE 10 illustrates the difference in microstructure between standard processing and attrition milling.

[0022] FIGURE 11 is an impedance plot illustrating the results of lower resonance peaks achieved when the material is prepared without zeta milling and without low firing.

[0023] FIGURE 12 is an impedance plot illustrating the results of lower resonance peaks achieved when the material is zeta milled and with high temperature firing.

[0024] FIGURE 13 is an impedance plot illustrating the results of higher resonant peaks achieved using methods of the preferred embodiments to process hexagonal ferrite material.

[0025] FIGURE 14 illustrates a telecommunication base station system incorporating a Co₂Z material formed in accordance with processing techniques of certain embodiments of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0026] Disclosed herein are techniques for manufacturing hexagonal ferrite materials, or hexaferrite materials, with enhanced resonant frequency available for antennas and other electronic devices. Magnetic materials are preferred in high frequency applications such as antennas, transformers, inductors, circulators, and absorbers because of the favorable material properties. Some of the desirable properties afforded by magnetic materials are favorable miniaturizing factors, reduced field concentration, and better impedance match. Hexagonal ferrite systems, in particular, are desirable because of their high magnetic permeability and absorption at microwave (100 MHz-20 GHz) frequencies.

[0027] Ceramic ferrites are generally ferromagnetic materials that incorporate the chemical compound iron(III) oxide (Fe₂O₃). Iron(III) oxide by itself typically has a high electrical conduction, which may result in high electrical and magnetic losses. These losses make iron(III) oxide not suitable for use in many electronic devices, especially those operating in radio frequency ranges. Therefore, other elements can be added to iron(III) oxide to lower the conduction while still keeping the positive qualities of the material. These additions lower the conductivity between local microcrystals, but keep the overall magnetic properties allowing ferrites to be useful in radio frequency devices.

[0028] As a material, ferrites tend to be hard and brittle, much like other ceramic materials. Also, most ferrites are black, inert, typically non-conductive and magnetic.

Because of these properties, ferrites are often used in high-frequency electronic components such as antennas, circulators, and resonators. Finally, ferrites can also be classified as either “hard” or “soft.”

[0029] Hard ferrites have high coercivity and are typically composed of iron, as well as barium or strontium oxides. Because they have high coercivity, hard ferrites also display high remanence after magnetization. These materials have a strong resistance to becoming demagnetized, and are most useful in the creation of permanent magnets. They can require up to 2000 oersted to demagnetize. Hard ferrites are also useful in creating permanent magnets because they conduct magnetic flux well, and have high magnetic permeability. Lastly, hard ferrites have high resistance to corrosion and tend to have a low purchasing price.

[0030] On the other hand, soft ferrites have low coercivity, meaning that the magnetization of the material can easily reduce direction without much energy loss. These materials are also highly resistive, thus preventing eddy currents and maintaining energy. Soft ferrites have a wide range of operating frequency, stability with time and temperature, low cost, and are light weight. They can be made from a large selection of materials with differing physical characteristics. Soft ferrites are extensively used in radio frequency applications due to them having low losses at high frequencies.

[0031] Hexagonal ferrite systems, such as in certain embodiments of the present invention, include crystal structures that are generally intergrowths between magnetoplumbite and spinel structures containing barium (Ba) or strontium (Sr), a divalent cation such as iron (Fe), cobalt (Co), nickel (Ni) or manganese (Mn) and trivalent Fe. Because many different atoms can be used, materials with considerably different magnetic properties can be formed. Figure 1 illustrates the crystal structure of a magnetoplumbite cell with the formula $\text{BaFe}_{12}\text{O}_{19}$. The barium atoms are located at the 102 positions, the iron atoms are located at the 103 positions, and the oxygen atoms are located at the 104 positions. Spinel is a class of minerals with the general formula $\text{A}^{2+}\text{B}_2^{3+}\text{O}_4^{2-}$ wherein A and B can be divalent, trivalent, or quadrivalent cations. Many ferrites are also spinels. Normal spinel crystal structures form into cubic closed-packed oxides and if the ions in the spinel are of similar sizes, the lattice energy of the structure is maximized. However, spinels can also have a structure known as an inverse spinel structure which is caused by the displacement of

certain atoms within the structure. In the inverse spinel structure, crystal field stabilization energies must be taken into account. Spinel can occur naturally and can be synthesized in a laboratory, such as in the case of thiospinels and selenospinel.

[0032] The intergrowths between magnetoplumbite and spinels form a hexagonal ferrite in a variety of different crystal structures based on the magnetoplumbite cell. These structures include M-phase ($\text{BaFe}_{12}\text{O}_{19}$), W-phase ($\text{BaCo}_2\text{Fe}_{16}\text{O}_{27}$), Y-phase ($\text{Ba}_2\text{Co}_2\text{Fe}_{12}\text{O}_{22}$), and Z-phase ($\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{42}$) hexagonal ferrite. However, the overall crystal structure is a result of the close packing of the oxygen ion layers.

[0033] The hexagonal ferrite materials can include Z type hexagonal ferrites such as $\text{M}^{\text{I}}_3\text{M}^{\text{II}}_2\text{Fe}_{24}\text{O}_{41}$, Y type hexagonal ferrites such as $\text{M}^{\text{I}}_2\text{M}^{\text{II}}_2\text{Fe}_{12}\text{O}_{22}$, W type hexagonal ferrites such as $\text{M}^{\text{I}}\text{M}^{\text{II}}_2\text{Fe}_{16}\text{O}_{27}$, U type hexagonal ferrites such as $\text{M}^{\text{I}}_4\text{M}^{\text{II}}_2\text{Fe}_{36}\text{O}_{60}$, X type hexagonal ferrites such as $\text{M}^{\text{I}}_2\text{M}^{\text{II}}_2\text{Fe}_{28}\text{O}_{46}$, and M type hexagonal ferrites such as $\text{M}^{\text{I}}\text{Fe}_{12-2x}\text{M}^{\text{II}}_x\text{M}^{\text{III}}_x\text{O}_{19}$, wherein M^{I} is barium (Ba) or strontium (Sr), and M^{II} is a divalent metal such as cobalt (Co), zinc (Zn), nickel (Ni), magnesium (Mg), manganese (Mn), or copper (Cu), M^{III} is a tetravalent metal such as titanium (Ti), zirconium (Zr), tin (Sn), germanium (Ge), silicon (Si), cerium (Ce), praseodymium (Pr), or hafnium (Hf). The appropriate addition of these elements will allow the materials to exhibit desirable characteristics.

[0034] One useful property of hexagonal ferrite materials is its favorable miniaturizing factors. The current trend in electronics is for the devices to be built smaller. Therefore, it is imperative to have materials that have properties favorable towards miniaturization. Some of these factors include minimal weight, long life before breaking down, insensitivity to external conditions such as shock and vibration, and other favorable properties making the material suitable for miniaturization. Also, as material becomes smaller, there is a need that the physical characteristics of the material will not change. Some materials contain properties that are affected by the size of the material as a whole, for example, a material may act differently when used as a bar as compared to when a quarter sized portion is used. Hexagonal ferrite materials contain minimal size based changes in physical characteristics.

[0035] The second useful property of hexagonal ferrite materials is the reduced field concentration. A material having a large field concentration can lead to large stresses within the material, thus negatively affecting physical properties. By having a reduced field

concentration within the hexagonal ferrite material, they can be used in applications with higher field concentrations and still adequately operate.

[0036] Another useful property of hexagonal ferrite materials is an improved impedance match. Impedance matching maximizes power transfer and minimizes reflections from a load. Loads can be from the electrical field or from any other field wherein energy is transferred between a source and a load. Ideally, the impedance of the source and the load would be purely resistive, wherein there would be no reflection. In some embodiments, the hexagonal ferrite material would have a perfect impedance match. This occurs when the impedance of the load is equal to the impedance of the signal source. Therefore, when a signal is directed at the material, the full power of the signal would arrive through the material. If the material has a low impedance match, most of the power would be reflected back out due to the differing impedance of the material and the medium transferring the signal. Transformers, filters, and resistive networks are all examples of devices that perform impedance matching.

[0037] Impedance bridging, wherein the impedences of the load and the source are not the same, can have drastic negative effects on radiofrequency connections. As mentioned above, when impedances don't match, a reflection is created. In radio frequency devices, this reflection can create a standing wave within the material. This standing wave can lead to a further waste of power and may cause frequency-dependent loss. Therefore, materials promoting impedance matching, such as hexagonal ferrites, are of important in radio frequency devices. Hexagonal ferrites allow an electronic device to run optimally while minimizing power lost.

Co₂Z Systems

[0038] Embodiments of the present invention disclose methods and processing techniques for improving performance characteristics of hexagonal ferrite materials used in high frequency applications. Certain preferred embodiments provide improved methods and processing techniques for manufacturing Z-phase hexagonal ferrite systems Ba₃Co₂Fe₂₄O₄₂, described herein as Co₂Z. Co₂Z systems have reduced magnetorestriction, improved resonant frequency, and extended magnetic permeability at higher frequencies. Co₂Z can have high performance into the ranges of 100-1000 MHz. Also, Co₂Z systems typically have

a non-cubic unit cell for a crystal structure, planar magnetization, and an anisotropic spin-rotation component to permeability.

[0039] Magnetostriction is a property of ferromagnetic materials that causes the material to change dimensions during magnetization. Magnetostriction occurs because ferromagnetic materials can be divided into many different magnetic domains. These domains each have their own uniform magnetization, wherein the magnetic moments of all of the atoms in a domain are aligned with each other in the same direction. As a ferromagnetic material is made up of many different magnetic domains, magnetizing the domains causes each of the domains to slightly shift. The overall net shift of the individual domains causes the material's change in dimensions. The dimensional change of a material in a magnetic field can lead to strain on the structure, which can reduce desirable properties within a system. The dimensional change can also cause losses due to frictional heating of the material during the change of shape. Therefore, the reduced magnetostriction of hexagonal ferrite materials, such as Co_2Z systems, makes it ideal for use in radio frequency applications.

[0040] A second characteristic of Co_2Z is that the material has a high resonant frequency. Resonance is the tendency of a system to oscillate at largest amplitudes at certain frequencies known as the system's resonance frequencies. At these specific frequencies, small driving forces can lead to large amplitude oscillations as the system stores vibrational energy from the original driving forces. A system can have one resonant frequency or multiple, distinct resonant frequencies.

[0041] Relative permittivity and permeability are also properties indicative of the performance of a magnetic material in high frequency applications. Co_2Z has favorable permittivity and permeability for use in electronic components. Relative permittivity (ϵ_r) is a dimensionless measurement of the electronic polarizability of a material as compared to the polarizability of free species. In other words, relative permittivity is the ratio of the capacitance of a capacitor using a material as a dielectric as compared to the same, or similar, capacitor that has a vacuum for the dielectric. Relative permittivity is measured by the formula:

$$\epsilon_r = \epsilon / \epsilon_0$$

wherein ϵ is the complex, frequency-dependent absolute permittivity and ϵ_0 is the vacuum

permittivity. Permittivity is also equivalent to the dielectric constant of a given material. For ferrite materials, the basic permittivity is in the order of 10. However, the bulk permittivity over the entire material can be very different. The difference in permittivity is caused by the conductivity inside the crystals of the material. Therefore, it is necessary to look at the bulk permittivity to receive an accurate result.

[0042] Relative permeability is a measure of the degree of magnetization of a material that responds linearly to an applied magnetic field relative to that of free species and is measured by the formula:

$$\mu_r = \mu / \mu_0$$

wherein μ is the complex, frequency-dependent absolute permittivity and ϵ_0 is the vacuum permittivity. Relative permeability is essentially the magnetic equivalent of permittivity wherein permeability measures the ability of a material to support the formation of a magnetic field. The overall equation for permeability is:

$$B = \mu H$$

wherein B is the magnetic field, μ is permeability, and H is the auxiliary magnetic field. Permeability is a scalar if the material is isotropic or a second rank tensor if the material is anisotropic.

[0043] Permeability also can be a function of temperature. Permeability increases with temperature until it reaches a maximum value and then drops off sharply. The temperature where the drop off occurs is known as the Curie temperature. Temperature dependence is an important feature in radio frequency applications. Preferably, a material would not have a large temperature dependence as electronic materials can be used in a variety of changing temperatures. If the properties of the material were to change drastically during use, the material would not make for an appropriate electronic.

[0044] Permeability can also be changed when a material is given a magnetic or thermal disturbance. When this occurs, permeability quickly rises to a peak. Upon reaching the peak, the permeability slowly decreases with time back to the original state. A material useful in the field of electronic devices would have permeability that had a low peak after disturbance.

[0045] Figure 2 is a graph illustrating the relationship between permeability and frequency, and illustrates how permeability can be broken up into real and imaginary

components. At low frequencies, the magnetic fields are proportional to each other and thus the imaginary component is just a scalar. However, at high frequencies, such as frequencies used in RF products, there is lag time between the magnetic field and the auxiliary magnetic field. Therefore, the permeability (μ) can be split into a real component (μ') and an imaginary component (μ''). Generally, real permeability (μ') can be separated into two components: spin rotational X_{sp} which is in response to high frequencies, and domain wall motion X_{dw} which is damped out at microwave frequencies. Permeability can be generally represented by

$$\mu' = 1 + X_{dw} + X_{sp}.$$

The $\tan \delta = \mu''/\mu'$ represents the loss tangent of the material, wherein the loss tangent quantifies the inherent dissipation of electromagnetic energy. Loss is usually split up into three components: hysteresis losses, eddy current losses, and residual losses. Hysteresis losses and eddy current losses are negligible at low frequencies. However, all three losses become a factor at high frequencies, and therefore they are necessary to look at when dealing with radio frequency electronics. The reciprocal of the loss factor gives the quality factor (Q).

[0046] Q is a dimensionless parameter that can characterize a resonator's bandwidth relative to its center frequency and can be defined as:

$$Q = 2\pi \times \frac{\text{Energy Stored}}{\text{Energy dissipated per cycle}} = 2\pi f_r \times \frac{\text{Energy Stored}}{\text{Power Loss}}$$

A system with a high Q stores a high level of energy as compared to the energy dissipated per cycle. A resonator with a high Q would resonate at greater amplitudes, but would have a small range of frequencies for resonating. Therefore, a material with a high Q would be more selective in resonating than a material with a low Q, thus allowing better filtration of other signals, but the resonator would be harder to tune due to the small range of frequencies. Moreover, a resonator with a sharp Q peak allows more channels to be inserted in a given bandwidth space. Therefore, many electronic devices, and therefore radio frequency devices, are better suited when they are formed from a material with a high Q due to the lack of interference from other signals.

[0047] Figures 3-4 illustrate the magnetic Q v. real permeability and complex permeability. In either case, magnetic Q decreases with an increase in permeability. Figure

3 illustrates the real permeability vs. magnetic Q at 700 MHz and at 400 MHz of a Co₂Z material formed in accordance with a method of the preferred embodiments. Figure 4 illustrates the permeability vs. magnetic Q of a Co₂Z material formed in accordance with a method of the preferred embodiment. However, as shown in Figure 3, the magnetic Q is almost 3 times as great in a 400 MHz than in a 700MHz system. In certain embodiments, the relationship between resonant frequency and saturation magnetization of Co₂Z is such that as frequency increases, the Q value first goes up and then falls while μ' and μ'' approximately follow the same pattern as in Figure 2.

[0048] Figure 5 schematically illustrates a cross section of Co₂Z wherein the material has varied directional rotational stiffness. The θ angle is the highest stiffness in the material. It is believed that the larger the difference in rotational stiffness, the greater the self-magnetization field and the greater the resonant frequency, which could push the resonant frequency into the microwave region. Permeability drops quickly above resonance frequency. The relationship between permeability and rotational stiffness can be represented by the formula:

$$(\mu_0 - 1)/4\pi = (1/3)(M_s/H_\theta^A + M_s/H_\phi^A).$$

μ_0 is the initial permeability, M_s is the saturation magnetization, H_θ^A is the anisotropy field in the θ direction, and H_ϕ^A is the anisotropy field in the ϕ direction. Large anisotropy fields (H_θ) are similar to applying an external magnetic field which increases resonant frequency, whereas small anisotropy fields (H_ϕ) improve permeability. For isotropic rotational stiffness in connection spinels and c-axis oriented hexagonal ferrites, the relationship can be represented as follows:

$$(\mu_0 - 1)/4\pi = (2/3)(M_s/H^A).$$

[0049] For cases where H_θ^A does not equal to H_ϕ^A :

$$f_{\text{res}}(\mu_0 - 1) = 4/3 \psi M_s [1/2 (H_\theta^A / H_\phi^A) + 1/2 (H_\phi^A / H_\theta^A)].$$

However, this leads to a more drastic drop off of magnetic Q as permeability increase. H_θ is generally strong in hexagonal ferrites, such as Co₂Z. As such, domain formation out of the basal plane is suppressed and the material becomes self-magnetizing.

[0050] For electronic components operating in the RF range, some of the important physical characteristics are the temperature coefficient of resonant frequency (τ_F)

and the dielectric constant (ϵ_r). Having the proper values for these physical characteristics allows for an electronic component to operate at an optimal level in differing environmental conditions. The disclosed materials exhibit favorable physical properties such as high or improved Q, improved dielectric constants, and a temperature coefficient of resonant frequency near 0, which are useful in the field of electronics.

[0051] The temperature coefficient of resonant frequency (τ_F), or temperature coefficient, embodies the relative change of resonant frequency when temperature is changed by 1K. The temperature coefficient is defined as:

$$R(T) = R(T_0)(1 + \alpha \Delta T)$$

In the electronic device market, especially in the field of radio frequency, materials having a τ_F near 0 are highly sought after. The τ_F , like many other physical characteristics, can change as the chemistry of the underlying material is altered. Adjusting τ_F can be done by adjusting the prevalence of certain elements within a structure, as the change of elements can cause or reduce strain on a crystal structure. A high positive or high negative value for τ_F in a material would limit the use of the material in radio frequency electronics as the resonant frequency would vary greatly based on temperature changes, thus limiting the use of a device in areas where temperatures range by a significant amount. If a τ_F value of 0 is achieved, the resonant frequency will remain constant regardless of the temperature of the material.

[0052] The dielectric constant (ϵ_r) is a dimensionless value for the relative permittivity of a material under certain conditions. It illustrates the amount of electric energy stored in a material by an applied voltage, relative to the amount stored in a vacuum. Moreover, ϵ_r can also be used to show the ratio of capacitance using the material as compared to a capacitor in a vacuum. If a material with a high ϵ_r is put into an electric field, the magnitude of the field will be greatly reduced within the material.

Magnetic Texturing

[0053] Certain aspects of the present disclosure provide processing techniques for increasing the permeability of Co_2Z at high frequencies. When preparing Co_2Z , spin rotation anisotropy is a major consideration for high frequency applications. In one implementation, the processing techniques involve methods of magnetic texturing of Co_2Z to result in a textured Co_2Z with improved magnetic properties. In one embodiment, the method of

magnetic texturing used in forming Co_2Z involves using a reaction sintering method, which includes the steps of aligning M-phase ($\text{BaFe}_{12}\text{O}_{19}$ uniaxial magnetization) with non-magnetic additives in a static magnetic field and reacting with BaO source and CoO to form Z-phase ($\text{Ba}_3\text{Me}_2\text{Fe}_{24}\text{O}_{42}$). Reaction sintering can produce dense covalent ceramic materials. Precise control of heating is necessary to perform reaction sintering, and the process can last for multiple weeks. While a material may gain substantial weight during the sintering, it will not create a large change in dimensional size, thus creating a dense material. Because the shape of the material can be maintained, this process can reduce the costs associated with machining and finishing.

[0054] Figure 6 illustrates the planar hexagonal anisotropy of Co_2Z . Therefore, the domains of the material are not aligned prior to any texturing. In one embodiment, the method of magnetic texturing used in forming Co_2Z involves using a rotating magnetic field method, which includes the steps of aligning Co_2Z phase (planar magnetization) with magnetic texturing occurring in a rotating magnetic field. By texturing in a rotating magnetic field, the degree of alignment, and thus permeability gain, is far superior. The degree of permeability increases for textured Co_2Z with higher degree of alignment formed in accordance with certain preferred embodiments.

[0055] This texturing technique can be used to form hexagonal ferrite materials with physical properties favorable towards their use in electronic devices. For example, the hexagonal ferrite materials can include Z type hexagonal ferrites such as $\text{M}^{\text{I}}_3\text{M}^{\text{II}}_2\text{Fe}_{24}\text{O}_{41}$, Y type hexagonal ferrites such as $\text{M}^{\text{I}}_2\text{M}^{\text{II}}_2\text{Fe}_{12}\text{O}_{22}$, W type hexagonal ferrites such as $\text{M}^{\text{I}}\text{M}^{\text{II}}_2\text{Fe}_{16}\text{O}_{27}$, U type hexagonal ferrites such as $\text{M}^{\text{I}}_4\text{M}^{\text{II}}_2\text{Fe}_{36}\text{O}_{60}$, X type hexagonal ferrites such as $\text{M}^{\text{I}}_2\text{M}^{\text{II}}_2\text{Fe}_{28}\text{O}_{46}$, and M type hexagonal ferrites such as $\text{M}^{\text{I}}\text{Fe}_{12-2x}\text{M}^{\text{II}}_x\text{M}^{\text{III}}_x\text{O}_{19}$, wherein M^{I} is barium (Ba) or strontium (Sr), and M^{II} is a divalent metal such as cobalt (Co), zinc (Zn), nickel (Ni), magnesium (Mg), manganese (Mn), or copper (Cu), M^{III} is a tetravalent metal such as titanium (Ti), zirconium (Zr), tin (Sn), germanium (Ge), silicon (Si), cerium (Ce), praseodymium (Pr), or hafnium (Hf). The addition of these elements will allow the materials to exhibit desirable characteristics.

Processing

[0056] Figure 7 illustrates a method 200 of forming a hexagonal ferrite material according to a preferred embodiment. In some embodiments, the hexagonal ferrite comprises Co_2Z . As shown in Figure 7, appropriate amounts of precursor materials are mixed together in Step 202. These precursor materials are reactants that may provide barium, cobalt, iron, one or more alkali metals, and oxygen that can form the magnetic material. In some aspects, at least a portion of the oxygen may be provided in the form of an oxygen-containing compound of barium (Ba), cobalt (Co), iron (Fe), or one or more alkali metals. For example, these elements may be provided in carbonate or oxide forms, or in other oxygen-containing precursor forms known in the art. In one or more aspects, one or more precursor materials may be provided in a non-oxygen-containing compound, or in a pure elemental form. In other aspects, oxygen could be supplied from a separate compound, such as, for example, H_2O_2 or from gaseous oxygen or air. For example, in one embodiment, BaCO_3 , Co_3O_4 , and Fe_2O_3 precursors are mixed in a ratio appropriate for the formation of Co_2Z (for example, about 22 wt. % BaCO_3 , about 6 wt. % Co_3O_4 , and about 72 wt. % Fe_2O_3) along with between about 0.06 wt. % and about 3.6 wt. % K_2CO_3 . These precursor compounds may be mixed or blended in water or alcohol using, for example, a Cowles mixer, a ball mill, or a vibratory mill. These precursors may also be blended in a dry form. The methods of chemical substitutions can be adapted to maximize frequency and can include adjusting the chemistry to improve permeability in Z-type structure without alignment.

[0057] The blended mixture may then be dried, if necessary, in Step 204. The mixture may be dried in any of a number of ways, including, for example, pan drying or spray drying. The dried mixture may then be heated in Step 206 at a temperature and for a period of time to promote calcination. For example, the temperature in the heating system used in heating Step 206 may increase at a rate of between about 20°C per hour and about 200°C per hour to achieve a soak temperature of about 1100°C - 1300°C , or preferably about 1100°C to 1250°C ., which may be maintained for about two hours to about twelve hours. The heating system may be, for example, an oven or a kiln. The mixture may experience a loss of moisture, and/or reduction or oxidation of one or more components, and/or the decomposition of carbonates and/or organic compounds which may be present. At least a portion of the mixture may form a hexaferrite solid solution.

[0058] The temperature ramp rate, the soak temperature, and the time for which the mixture is heated may be chosen depending on the requirements for a particular application. For example, if small crystal grains are desired in the material after heating, a faster temperature ramp, and/or lower soak temperature, and/or shorter heating time may be selected as opposed to an application where larger crystal grains are desired. In addition, the use of different amounts and/or forms of precursor materials may result in different requirements for parameters such as temperature ramp rate and soaking temperature and/or time to provide desired characteristics to the post-heated mixture.

[0059] After heating, the mixture, which may have formed agglomerated particles of hexaferrite solid solution, may be cooled to room temperature, or to any other temperature that would facilitate further processing. The cooling rate of the heating system may be, for example, 80°C. per hour. In step 208, the agglomerated particles may be milled. Milling may take place in water, in alcohol, in a ball mill, a vibratory mill, or other milling apparatus. In some embodiments, the milling is continued until the median particle diameter of the resulting powdered material is from about one to about four microns, although other particle sizes, for example, from about one to about ten microns in diameter, may be acceptable in some applications. In a preferred embodiment, high energy milling is used to mill the particles to a fine particle size of 0.2 to 0.9 microns in diameter. In other embodiments, a fine grain hexagonal ferrite powder is formed. This particle size may be measured using, for example, a sedigraph or a laser scattering technique. A target median particle size may be selected to provide sufficient surface area of the particles to facilitate sintering in a later step. Particles with a smaller median diameter may be more reactive and more easily sintered than larger particles. In some methods, one or more alkali metals or alkali metal precursors or other dopant materials may be added at this point rather than, or in addition to, in step 202.

[0060] The powdered material may be dried, if necessary, in step 210 and the dried powder may be pressed into a desired shape using, for example, a uniaxial press or an isostatic press in step 212. The pressure used to press the material may be, for example, up to 80,000 N/m, and is typically in the range of from about 20,000 N/m to about 60,000 N/m. A higher pressing pressure may result in a more dense material subsequent to further heating than a lower pressing pressure.

[0061] In some embodiments, the processing technique for forming Co_2Z includes making Z phase Fe deficient to inhibit reduction of Fe, as the dielectric and magnetic loss is increased by reduction of Fe ($\text{Fe}^{3+} \rightarrow \text{Fe}^{2+}$) at high temperatures. The processing technique includes the step of heat treatment or annealing in oxygen to inhibit reduction of Fe and cause $\text{Fe}^{2+} \rightarrow \text{Fe}^3$. In other embodiments, the processing technique includes doping the Co_2Z with additives, such as potassium and alkali metals, to increase the resonance frequency, and hence increase Q at higher frequency ranges.

[0062] In step 214, the pressed powdered material may be sintered to form a solid mass of doped hexaferrite. The solid mass of doped hexaferrite may be sintered in a mold having the shape of a component desired to be formed from the doped hexaferrite. Sintering of the doped hexaferrite may be performed at a suitable or desired temperature and for a time period sufficient to provide one or more desired characteristics, such as, but not limited to, crystal grain size, level of impurities, compressibility, tensile strength, porosity, and in some cases, magnetic permeability. Preferably, the sintering conditions promote one or more desired material characteristics without affecting, or at least with acceptable changes, to other undesirable properties. For example, the sintering conditions may promote formation of the sintered doped hexaferrite with little or minimal iron reduction. In one embodiment, the temperature used in the sintering step 214 is preferably between 1100°C to 1250°C . According to some embodiments, the temperature in the heating system used in the sintering step 214 may be increased at a rate of between about 20°C per hour and about 200°C per hour to achieve a soak temperature of about 1150°C - 1450°C or about 1100°C to 1150°C or about 1100°C - 1250°C which may be maintained for about two hours to about twelve hours. The heating system may be, for example, an oven or a kiln. A slower ramp, and/or higher soak temperature, and/or longer sintering time may result in a more dense sintered material than might be achieved using a faster temperature ramp, and/or lower soak temperature, and/or shorter heating time. The material may optionally be crush pressed as in step 216. Increasing the density of the final sintered material by making adjustments, for example, to the sintering process can be performed to provide a material with a desired magnetic permeability, saturation magnetization, and/or magnetostriction coefficient. According to some embodiments of methods according to the present invention, the density range of the sintered hexaferrite may be between about 4.75 g/cm^3 and about 5.36 g/cm^3 . A desired

magnetic permeability of the doped hexaferrite may also be achieved by tailoring the heat treatment of the material to produce grains with desired sizes.

[0063] The grain size of material produced by embodiments of the above method may vary from between about five micrometers and one millimeter in diameter depending upon the processing conditions, with even larger grain sizes possible in some aspects of methods according to the present invention. In some aspects, each crystal of the material may comprise a single magnetic domain. Both doped Co_2Z and un-doped Co_2Z may be members of the planar hexaferrite family, having a Z-type ferrite crystal structure.

[0064] This processing technique can be used to form hexagonal ferrite materials. For example, the hexagonal ferrite materials can include Z type hexagonal ferrites such as $\text{M}^{\text{I}}_3\text{M}^{\text{II}}_2\text{Fe}_{24}\text{O}_{41}$, Y type hexagonal ferrites such as $\text{M}^{\text{I}}_2\text{M}^{\text{II}}_2\text{Fe}_{12}\text{O}_{22}$, W type hexagonal ferrites such as $\text{M}^{\text{I}}\text{M}^{\text{II}}_2\text{Fe}_{16}\text{O}_{27}$, U type hexagonal ferrites such as $\text{M}^{\text{I}}_4\text{M}^{\text{II}}_2\text{Fe}_{36}\text{O}_{60}$, X type hexagonal ferrites such as $\text{M}^{\text{I}}_2\text{M}^{\text{II}}_2\text{Fe}_{28}\text{O}_{46}$, and M type hexagonal ferrites such as $\text{M}^{\text{I}}\text{Fe}_{12-2x}\text{M}^{\text{II}}_x\text{M}^{\text{III}}_x\text{O}_{19}$, wherein M^{I} is barium (Ba) or strontium (Sr), and M^{II} is a divalent metal such as cobalt (Co), zinc (Zn), nickel (Ni), magnesium (Mg), manganese (Mn), or copper (Cu), M^{III} is a tetravalent metal such as titanium (Ti), zirconium (Zr), tin (Sn), germanium (Ge), silicon (Si), cerium (Ce), praseodymium (Pr), or hafnium (Hf). The addition of these elements will allow the materials to exhibit desirable characteristics.

[0065] Figure 8 illustrates a method 300 of forming textured Co_2Z according to another embodiment adapted to reduce the magnetorestriction and improve the resonant frequency of the material. The method 300 begins with step 302 in which a fine grain hexagonal ferrite powder is formed. In one implementation, the fine grain hexagonal ferrite powder is a barium cobalt ferrite Z-phase (Co_2Z) powder. The Co_2Z powder can be synthesized using a chemical process known in the art such as co-precipitation. The Co_2Z can also be synthesized via sol-gel, calcining, and mechanical milling using a Netzsch zeta-mill or the like. In one embodiment, the Co_2Z powder has particle sizes of less than about 1 micron and surface areas of greater than about $6 \text{ m}^2/\text{g}$. In another embodiment, the Co_2Z powder has an average particle size of less than about 1 micron and an average surface area of greater than about $6 \text{ m}^2/\text{g}$. In a preferred implementation, the Co_2Z powder has a median particle size of between 300-600 nm, and a surface area of greater than about $15 \text{ m}^2/\text{g}$. The resulting material is preferably a fine grained hexagonal ferrite material having a density in

the range of about 70%-100% of the theoretical density. It will be appreciated that the hexagonal ferrite powder can also comprise Y, W, U, X, or M phase hexagonal ferrite materials, depending on the application. In some embodiments, nanopowders such as silica (SiO_2) and/or Alumina (Al_2O_3) may be added to modify the grain size and further improve the resonant frequency.

[0066] As Figure 8 further shows, the method 300 further comprises step 304 in which the hexagonal ferrite powder is compacted by a known process such as cold isostatic pressing, uniaxial pressing, extrusion, or the like. As shown in step 306, the hexagonal powder is subsequently fired at a temperature between about 1100° C to 1250° C., which is lower than the standard, conventional sintering temperature for the same material. The resulting material is preferably a fine grained hexagonal ferrite material and is shown in Figure 9. The formed hexagonal ferrite material has resonant frequencies at higher value than that of an equivalent hexagonal ferrite material synthesized using conventional ceramic processing methods.

[0067] In one implementation, the method further includes doping the hexagonal ferrite with small amounts of dopants such as K, Na, Rb, or Ca. The addition of these impurities may result in changes to properties of the material such as magnetic moment, magnetic loss tangent, electrical permittivity, magnetic permeability, peak magnetization and other physical characteristics of the material.

[0068] In some other embodiments, the processing technique for forming Co_2Z includes forming fine grain hexagonal ferrite particles. Figure 10 illustrates the microstructure difference between standard processing and attrition milling, wherein the attrition milling results in much smaller grain size than in standard milling. The smaller grain size promotes the favorable properties of the hexagonal ferrite material. The process involves using high energy milling to reduce the particle size. The following chart shows that in one embodiment, high energy milling is used to produce Co_2Z particle size in the range of 0.2 to 0.9 microns and surface area of 8 – 14 m^2/g . In this embodiment, the firing temperature is preferably 1150 to 1250°C.

Process	Particle Size	Surface Area	Firing Temp.	Grain Size (Intercept Method)
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Standard Milling	1-5 microns	1-3 m ² /g	1250-1350°C	10-30 microns
High Energy Milling	0.2-0.9 microns	8-14 m ² /g	1150-1250°C	2-15 microns

[0069] This processing technique can be used to form hexagonal ferrite materials. For example, the hexagonal ferrite materials can include Z type hexagonal ferrites such as $M^I_3M^{II}_2Fe_{24}O_{41}$, Y type hexagonal ferrites such as $M^I_2M^{II}_2Fe_{12}O_{22}$, W type hexagonal ferrites such as $M^IM^{II}_2Fe_{16}O_{27}$, U type hexagonal ferrites such as $M^I_4M^{II}_2Fe_{36}O_{60}$, X type hexagonal ferrites such as $M^I_2M^{II}_2Fe_{28}O_{46}$, and M type hexagonal ferrites such as $M^I_2Fe_{12-2x}M^{II}_xM^{III}_xO_{19}$, wherein M^I is barium (Ba) or strontium (Sr), and M^{II} is a divalent metal such as cobalt (Co), zinc (Zn), nickel (Ni), magnesium (Mg), manganese (Mn), or copper (Cu), M^{III} is a tetravalent metal such as titanium (Ti), zirconium (Zr), tin (Sn), germanium (Ge), silicon (Si), cerium (Ce), praseodymium (Pr), or hafnium (Hf). The addition of these elements will allow the materials to exhibit desirable characteristics.

[0070] The improved Q component may then be finished or machined to have desirable features or dimensions or to remove undesirable portions created during the formation process. For example, machining can involve creating one or more openings in the body of the component.

Examples

[0071] Figures 11-13 illustrate impedance plots showing a Co_2Z powder. It can be seen that Co_2Z demonstrates a relatively constant magnetic permeability at lower frequencies. At higher frequencies, the material demonstrates a rise in magnetic permeability leading to a peak, followed by a rapid drop off as in magnetic permeability as frequency continues to increase. The peak of magnetic permeability is the resonant frequency of the material. Figure 11 is the impedance plot when the Co_2Z is prepared without zeta milling and without low temperature firing. Figure 12 illustrates the impedance plot when Co_2Z is prepared with zeta milling and with high temperature firing, at around 1140°. Finally, Figure 13 illustrates the impedance plot when Co_2Z is prepared using the preferred embodiments, having a median particle size of about 2-3 microns and processed through a zeta-mill and fired at about 1100° C. As shown in Figure 13, the resonant peak, or maximum of the

imaginary permeability curve, is shifted to higher frequencies with zeta milling and low firing temperatures. Without wishing to be bound by theory, it is believed that the hexagonal ferrite materials formed by the preferred processing techniques do not have or have very small internal stress field leading to magnetorestriction. The hexagonal ferrite material formed according to methods described herein can be incorporated in a variety of RF devices such as high frequency antennas, inductors, and transformers.

[0072] A comparison between Figure 11 with Figures 12 and 13 establishes that zeta-milling and firing the Co_2Z powder increases the resonant frequency of the material. Further, a comparison of Figures 12 and 13 shows that lowering the firing temperature from 1140° to 1100° leads to a further increase in the resonant frequency of the material. This increase in resonant frequency shows that RF device components made from zeta-milled and low fired Co_2Z may be capable of retaining their magnetic permeability and operating in a frequency range higher than, or in a broader frequency range than, that of similar devices or device components made from un-milled and higher-fired Co_2Z .

[0073] Figures 11-13 also illustrate the effect of Zeta-milling and low firing on the imaginary component of the complex relative magnetic permeability, μ'' , which corresponds to energy loss in the material at high frequencies. In Figures 11-13 it can be observed that maximum of the imaginary permeability curve, the resonant peak, is shifted to higher frequencies when the Co_2Z material is processed with powder that has been zeta-milled and low fired. The combination of Figures 11-13 illustrate that the Co_2Z formed by certain embodiments of this disclosure are capable of retaining their magnetic permeability at a higher frequency than that of Co_2Z formed by conventional methods. The material may also be able to operate at a broader frequency than materials formed by conventional methods.

Application of the material

[0074] One or more embodiments of the disclosed technique provide a framework to develop real world devices in the field of electronics, including, but not limited to, radio frequency. Electronic components used in radio frequency preferably have reduced magnetorestriction, extended permeability at higher frequencies, and improved resonant

frequency. Embodiments of the present invention provide for a hexagonal ferrite material having such desirable qualities.

[0075] Materials formed in accordance with preferred embodiments of the present invention have applications in electronic devices. The enhanced resonant frequency Co_2Z formed in accordance with certain embodiments described herein can be incorporated into numerous types of RF devices including antennas. Figure 14 illustrates a telecommunication base station system 500 comprising a transceiver 502, a synthesizer 504, an RX filter 506, a TX filter 508, and magnetic isolators 510 and an antenna 512. In preferred implementations, the antenna 512 comprises a Co_2Z material made in accordance with certain embodiments described in this disclosure. Certain embodiments of the present invention are especially useful in helical antennas.

[0076] Provided herein are various non-limiting examples of composition, materials, and methods of preparing the materials for electronic applications. While the above detailed description has shown, described, and pointed out novel features of the invention as applied to various embodiments, it will be understood that various omissions, substitutions, and changes in the form and details of the device or process illustrated may be made by those skilled in the art without departing from the spirit of the invention. As will be recognized, the present invention may be embodied within a form that does not provide all of the features and benefits set forth herein, as some features may be used or practiced separated from others.

WHAT IS CLAIMED IS:

1. A method of increasing the resonant frequency of a hexagonal ferrite material, said method comprising:
forming a fine grain hexagonal ferrite powder; and
firing the hexagonal ferrite powder at a temperature lower than 1250°C to form a hexagonal ferrite material having reduced magnetorestriction.
2. The method of claim 1 further comprising compacting the hexagonal ferrite powder prior to firing.
3. The method of claim 1 wherein the fine grain hexagonal ferrite powder has an average particle size of less than 1 micron.
4. The method of claim 3 wherein the fine grain hexagonal ferrite powder has an average particle size of between 0.2 to 0.9 micron.
5. The method of claim 3 wherein the hexagonal powder has an average particle size of between 300-600 nm.
6. The method of claim 1 wherein the fine grain hexagonal ferrite powder has an average surface area of greater than 6 m²/g.
7. The method of claim 1 wherein the sintering temperature is between 1100 and 1250 °C.
8. The method of claim 5 wherein the fine grain hexagonal ferrite powder has an average surface area of greater than 15 m²/g.
9. The method of claim 1 wherein the fine grain hexagonal ferrite powder can be formed by a process selected from the group consisting of co-precipitation, sol-gel, and mechanical milling.
10. The method of claim 1 wherein the hexagonal ferrite powder comprises Co₂Z.
11. The method of claim 1 wherein the hexagonal ferrite material has resonant frequencies at higher value than that of an equivalent hexagonal ferrite material synthesized using conventional ceramic processing methods.
12. An RF device incorporating the hexagonal ferrite material formed by the method of Claim 1.
13. An antenna incorporating the hexagonal ferrite material formed by the method of Claim 1.

14. A method of increasing the permeability of hexagonal ferrite by magnetic texturing, said method comprising:

aligning M-phase hexagonal ferrite with non-magnetic additives in a static magnetic field;

sintering said aligned M-phase hexagonal ferrite with barium oxide and cobalt oxide to form a Z-phase hexagonal ferrite.

15. The method of claim 14 wherein said M-phase hexagonal ferrite comprises $M^I\text{Fe}_{12-2x}M^{II}_xM^{III}_x\text{O}_{19}$, where M^I is selected from the group consisting of barium (Ba) and strontium (Sr), where M^{II} is selected from the group consisting of cobalt (Co), zinc (Zn), nickel (Ni), magnesium (Mg), manganese (Mn), and copper (Cu), and where M^{III} is selected from the group consisting of titanium (Ti), zirconium (Zr), tin (Sn), germanium (Ge), silicon (Si), cerium (Ce), praseodymium (Pr), and hafnium (Hf).

16. The method of claim 15 wherein said M-phase hexagonal ferrite comprises $\text{BaF}_{12}\text{O}_{19}$.

17. The method of claim 14 wherein said Z-phase hexagonal ferrite comprises $M^I_3M^{II}_2\text{Fe}_{24}\text{O}_{41}$ where M^I is selected from the group consisting of barium (Ba) and strontium (Sr), where M^{II} is selected from the group consisting of cobalt (Co), zinc (Zn), nickel (Ni), magnesium (Mg), manganese (Mn), and copper (Cu).

18. The method of claim 17 wherein said Z-phase hexagonal ferrite comprises $\text{Ba}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$.

19. The method of claim 14 wherein said aligned M-phase hexagonal ferrite is sintered at a temperature lower than 1250°C.

20. An RF device incorporating the hexagonal ferrite material formed by the method of Claim 14.

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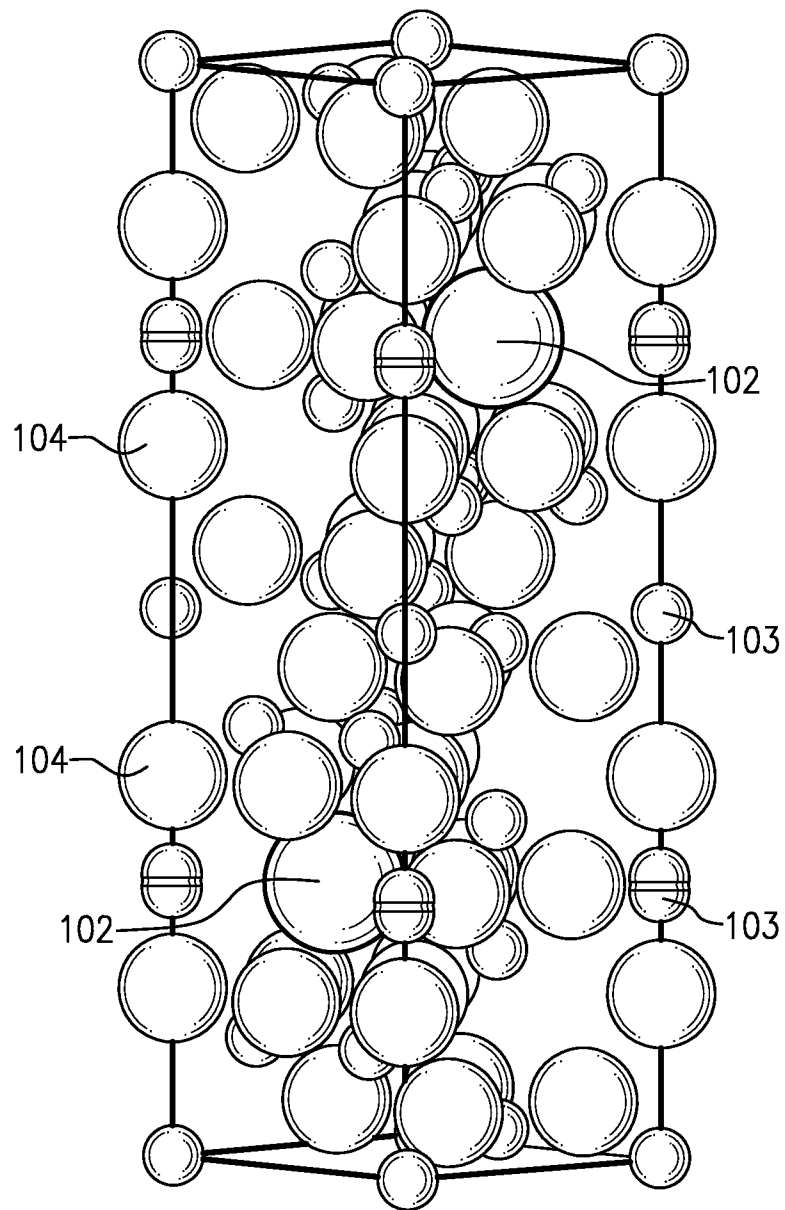
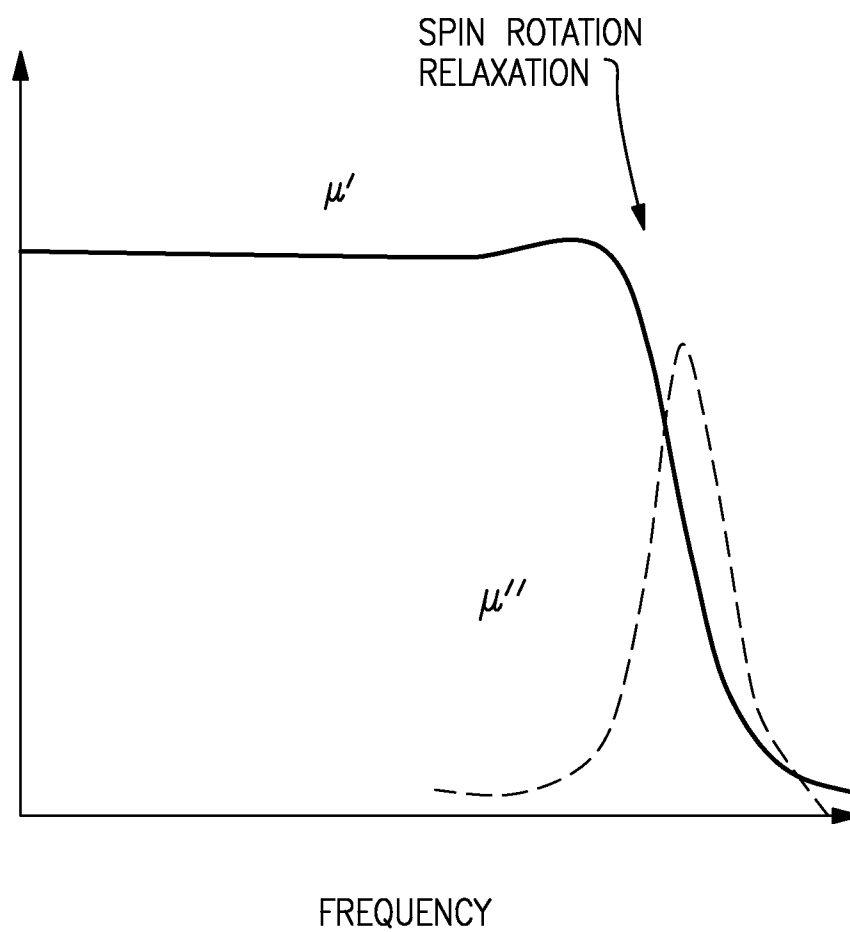


FIG.1

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**FIG.2**

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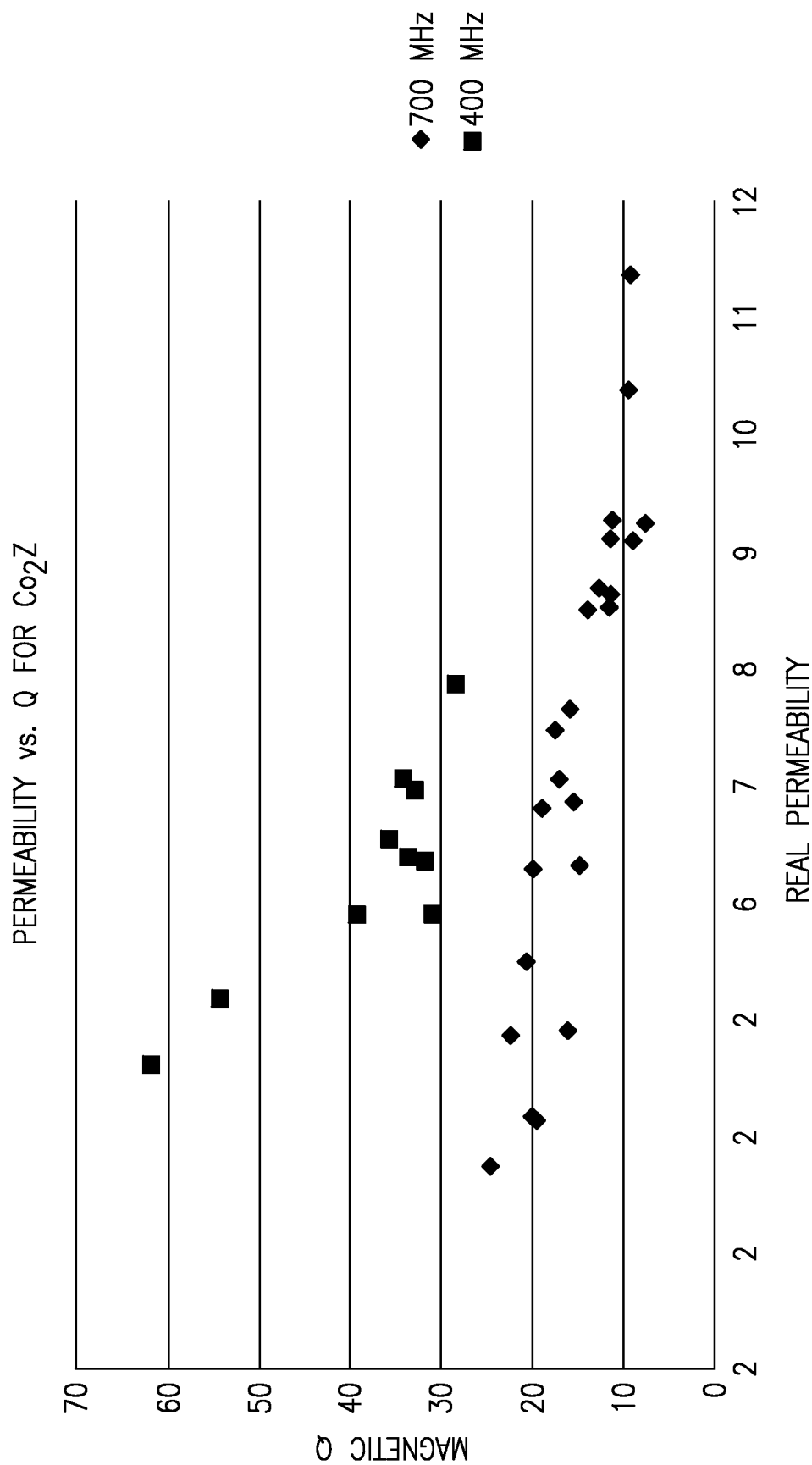


FIG.3

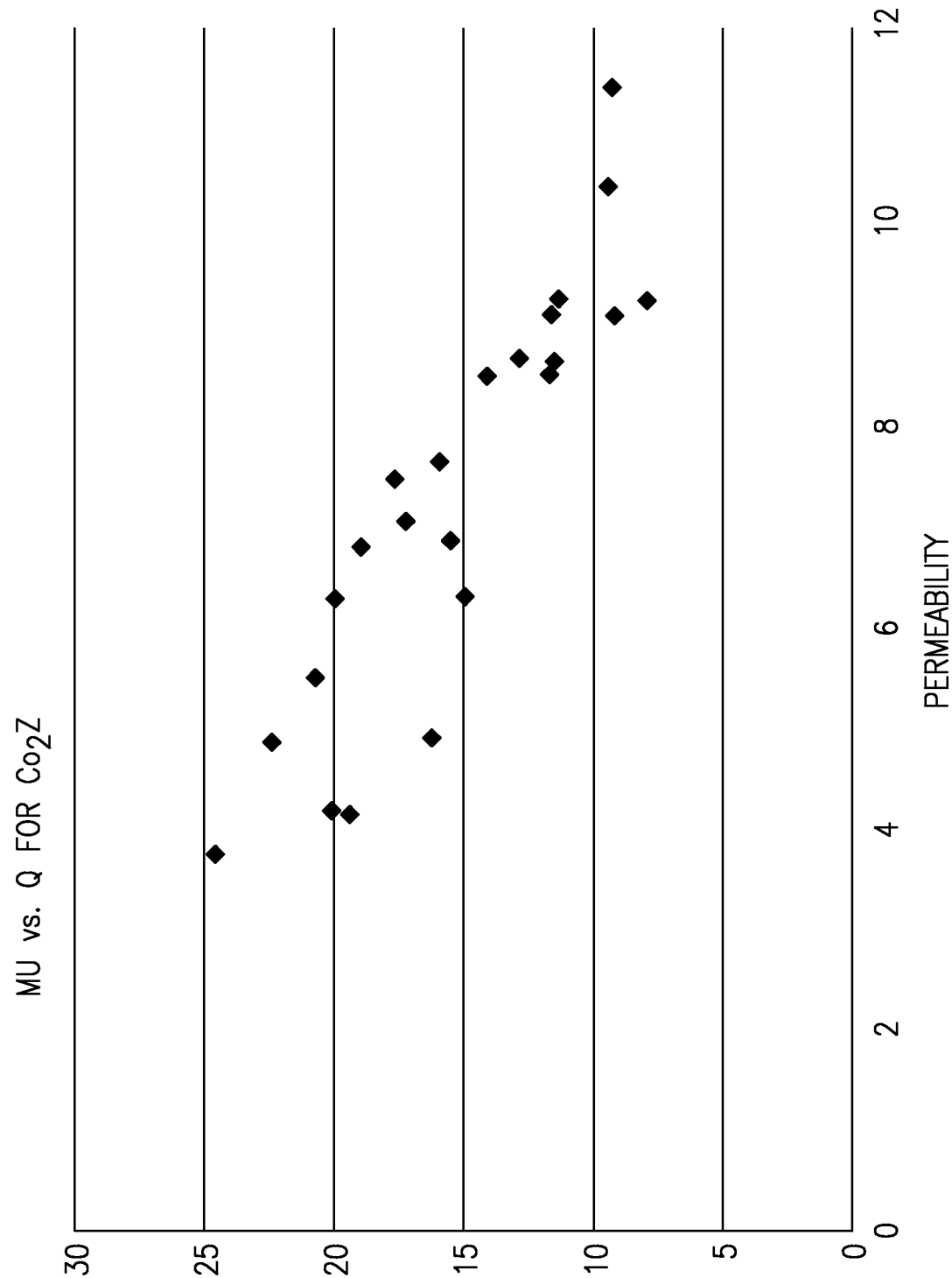


FIG.4

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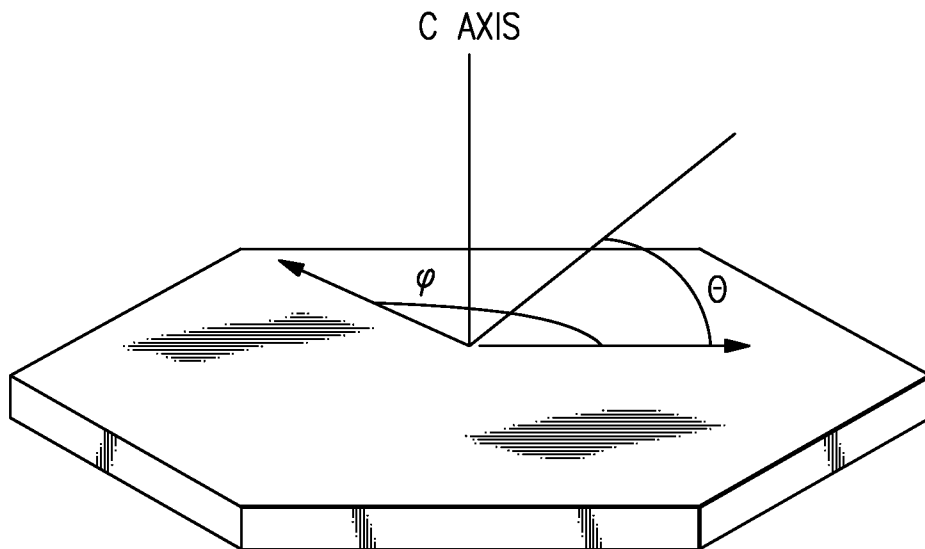


FIG. 5

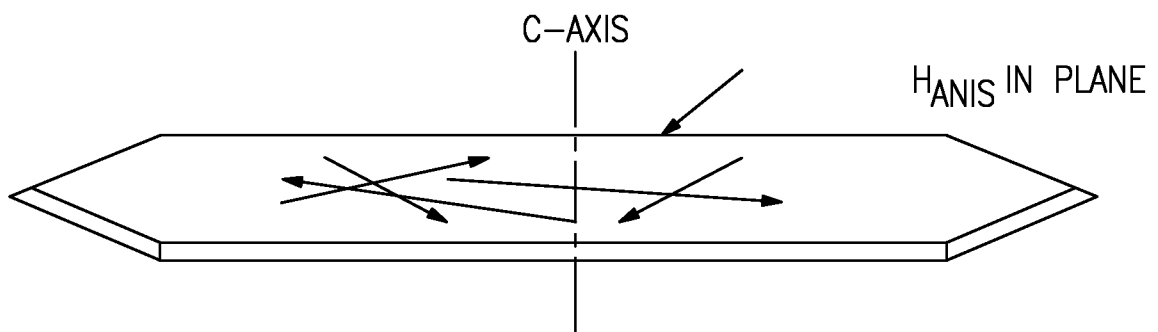
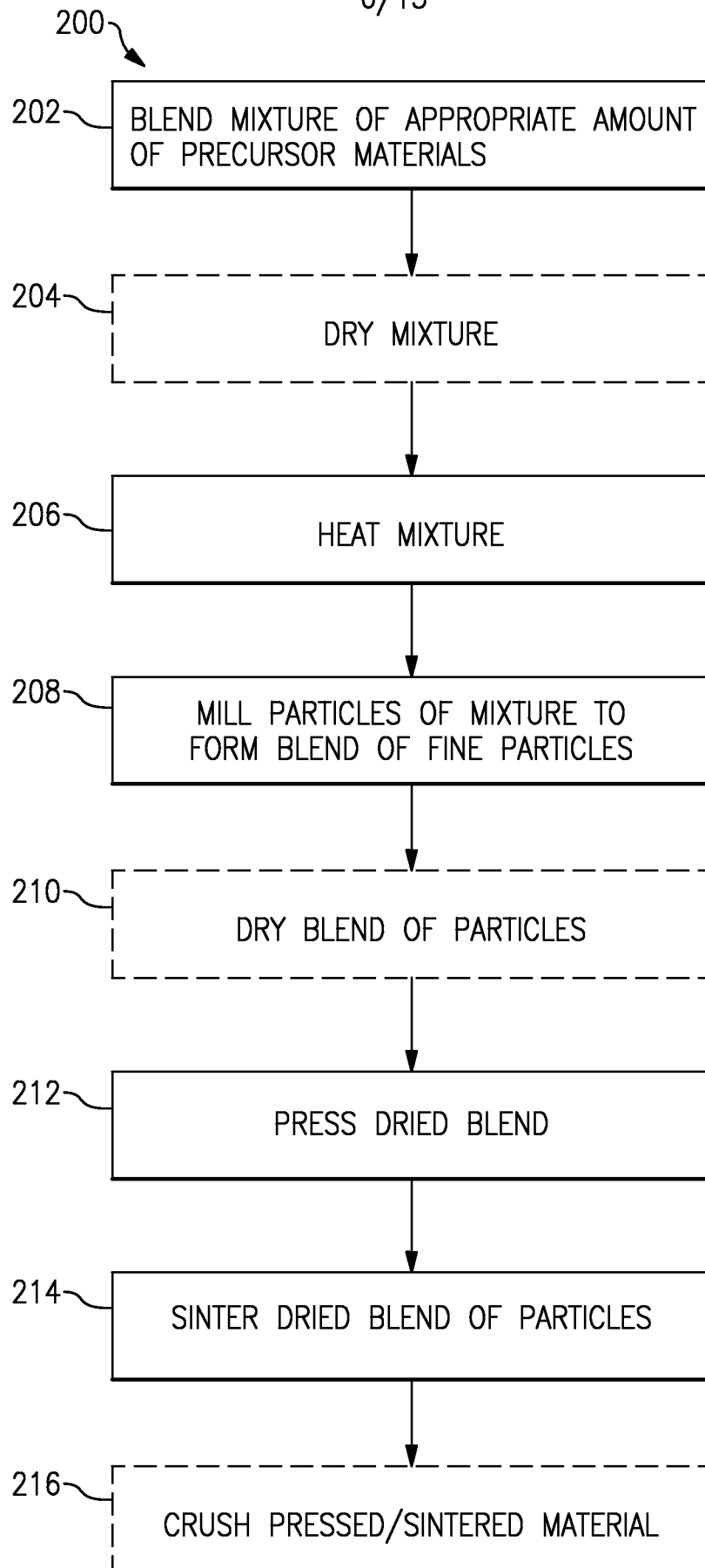
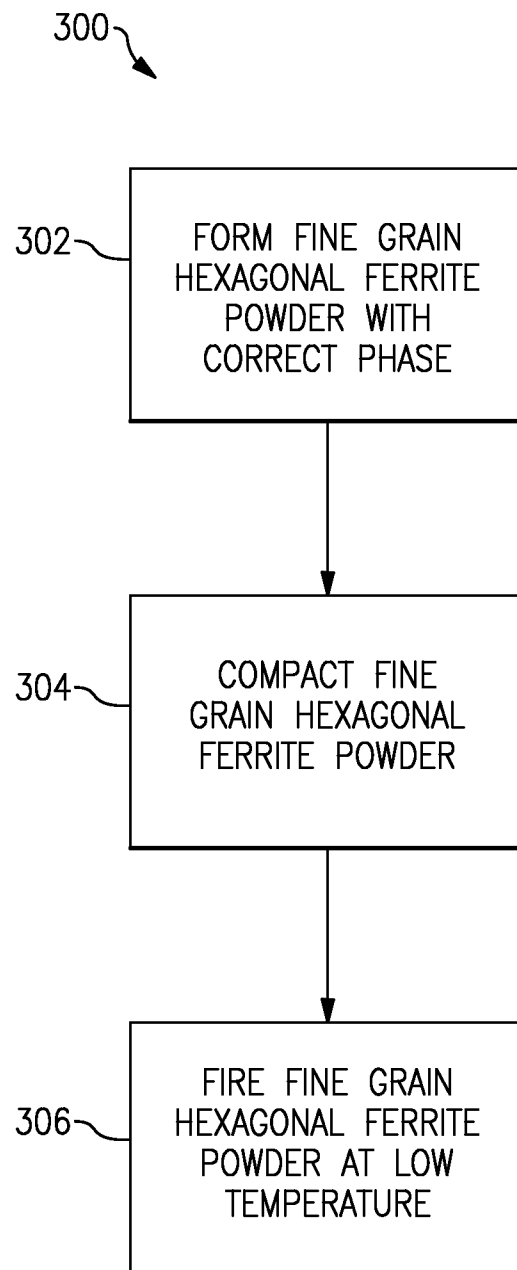


FIG. 6

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**FIG.7**

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**FIG.8**

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FIG.9

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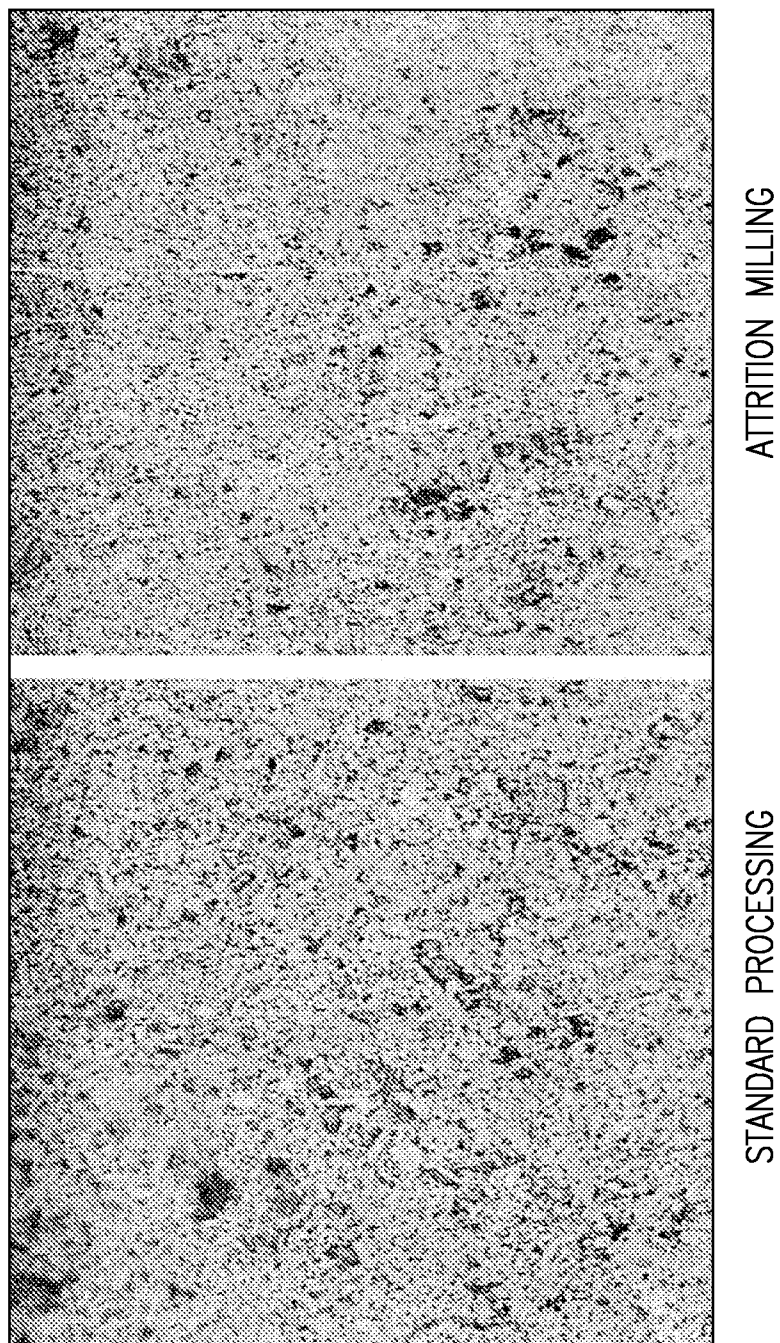


FIG.10

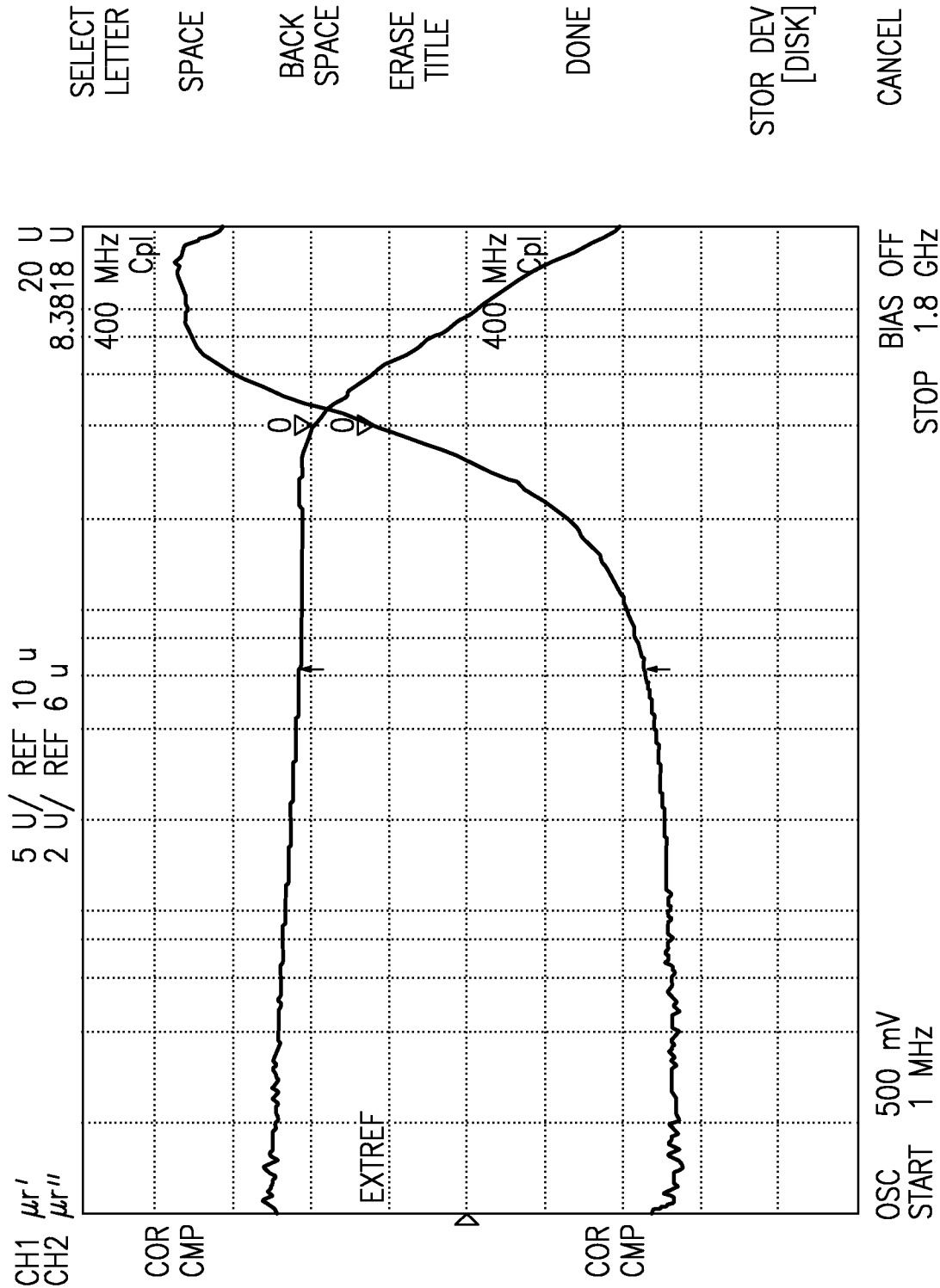


FIG.11

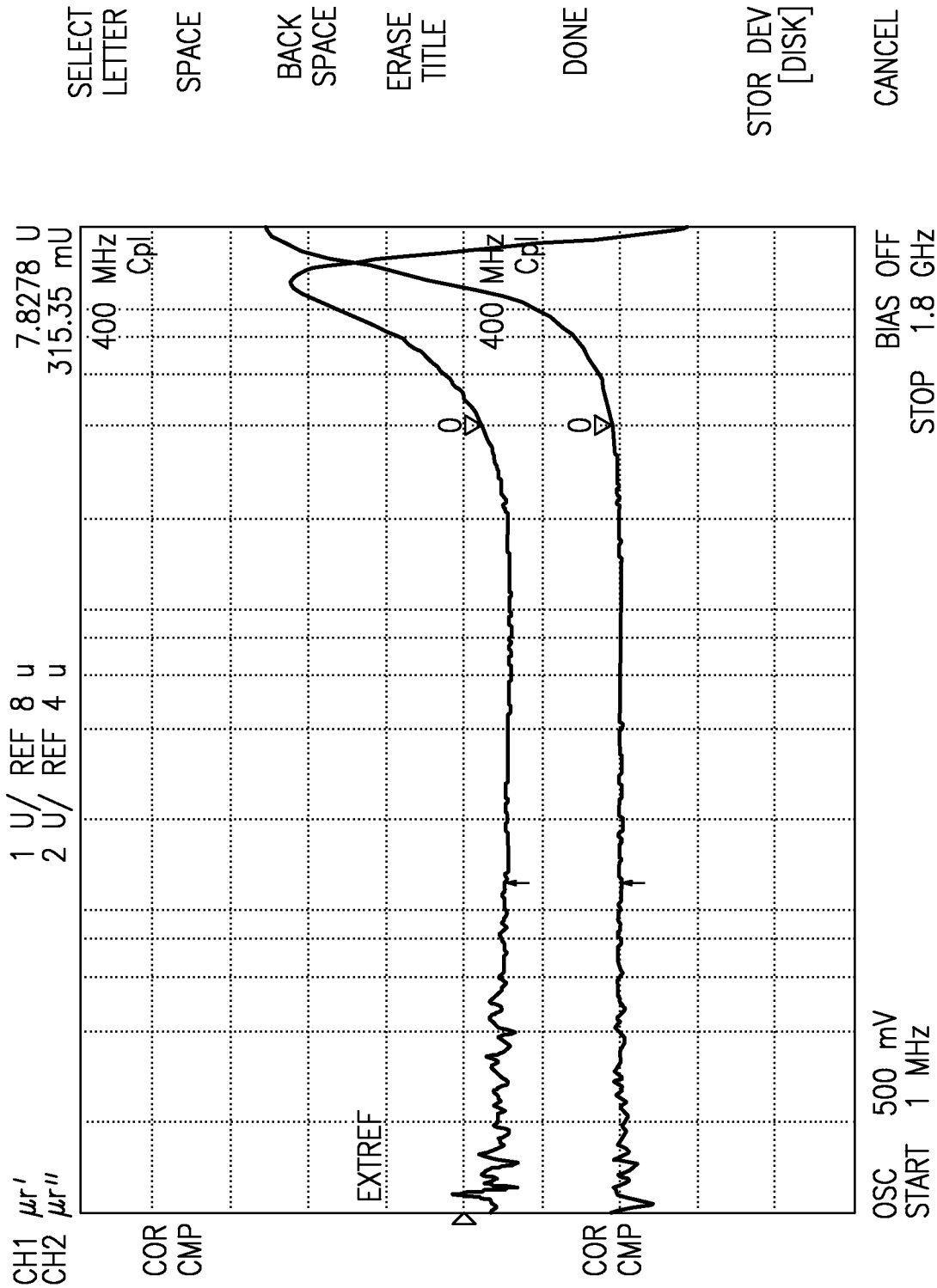


FIG.12

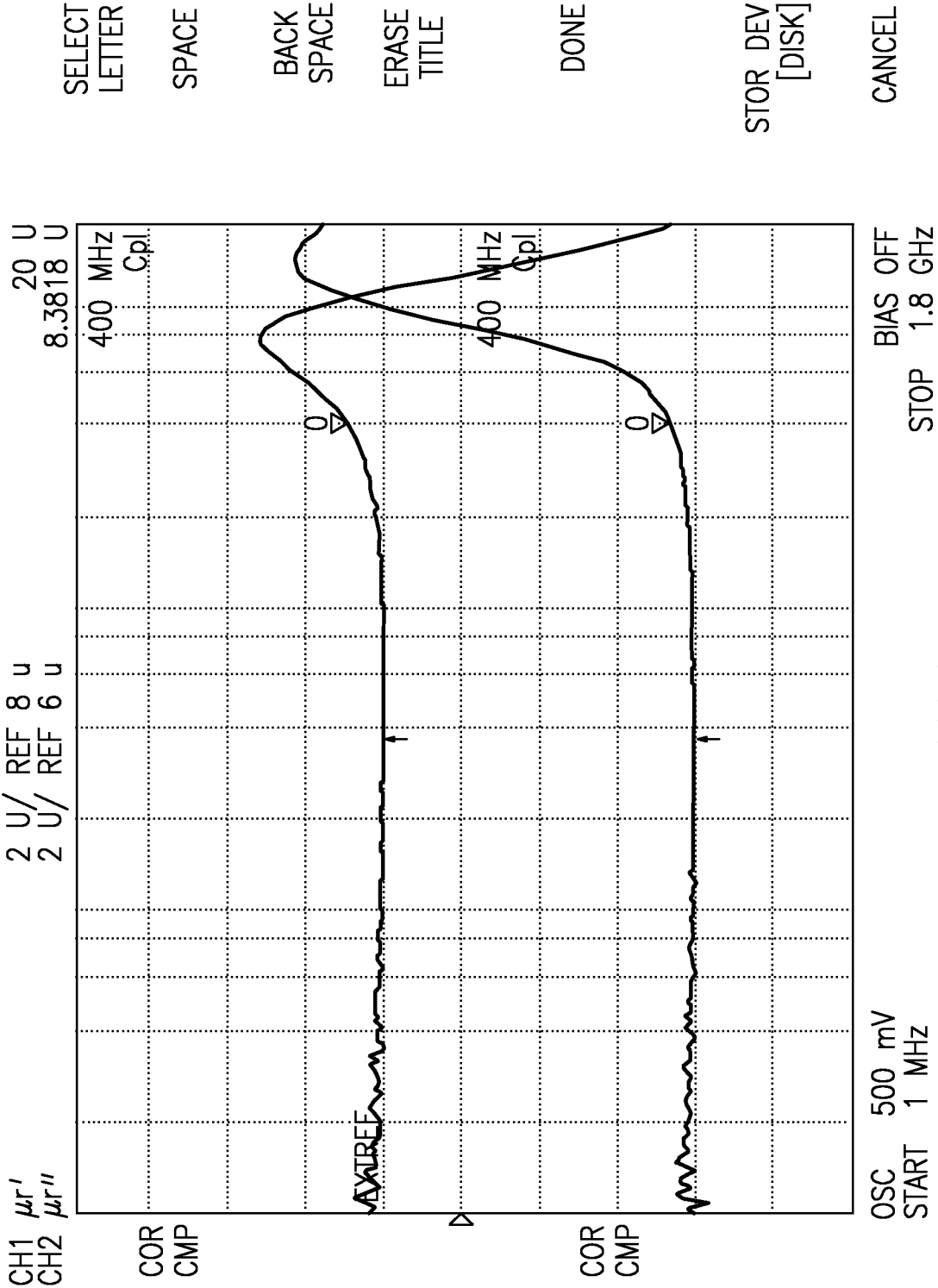


FIG.13

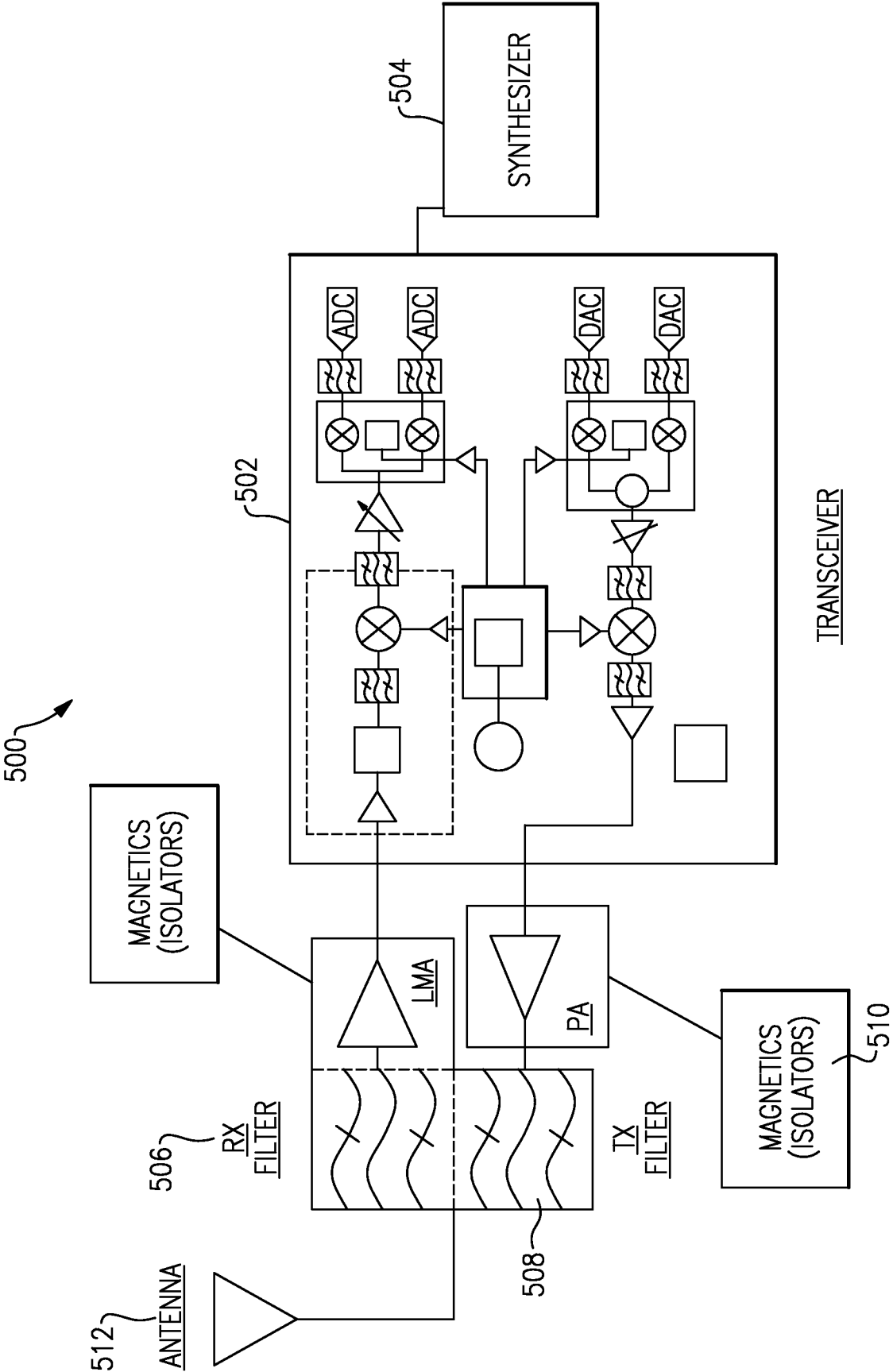


FIG.14