"Q-factor improvement of integrated inductors using high aspect ratio ferromagnetic nanowires"

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Abstract
We fabricated a planar inductor onto a substrate made of high aspect ratio ferromagnetic nickel nanowires in a self-supported alumina nanoporous membrane. We observe a simultaneous increase of the inductance value and the quality factor up to 7 GHz, thanks to the large amount of ferromagnetic material and the nanoscale of the wires limiting conducting losses. Our device shows the largest increase reported in the literature for such ferromagnetic inductors: +30% for the inductance value and +23% for the quality factor. Even more, this technology offers great advantages as an easy integration in miniaturized topologies and its tunability to a magnetic field to broaden the desired frequency range. Our analytical model predicts that the increase of quality factor can be maximized up to 35% by an optimization of the pores filling.

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low-profile on-metal tag, as the overall tag thickness is 2 mm only.

The analysis in this letter has been focused on the power transmission coefficient maximization through the tuning of the tag antenna input impedance.

Another relevant aspect in the design of a RFID tag is its reading range. This was measured for the two original tags in three different conditions: in free space, when the inlay is placed on a conductive sheet, and finally after the tuning phase when they are stuck on the magneto-dielectric laminate. Reading range measurements were performed in an anechoic chamber. In free space condition, both tags were read at a distance up to around 3.5 m. As expected, when the tags are placed on an aluminum sheet, they were not detectable even at distances <5 cm, while both the trimmed tuned tags are readable at a distance up to around 75 cm. Although the impedance matching condition is satisfied, the latter distance is five times shorter than the free-space one. This is due the losses introduced by the magneto-dielectric laminate. Indeed, it is well known that tag reading range performance is proportional to the tag antenna gain (see Friis free-space transmission formula in Ref. 1). For the two modified tags on the Emerson&Cuming Eccosorb MCS-U laminate, a radiation efficiency (averaged value in the UHF band) of around 2% has been obtained against the value of around 95% for the free-space configuration. This strong efficiency reduction causes the antenna gain and, consequently, the reading range decrease. For the sake of completeness, it is worth mentioning that a reading range of around 20 cm was measured when the two original (not trimmed yet) tags are placed on the magneto-dielectric stack-up. In this case, the input impedance of the two antennas does not conjugate match the chip one and a further reading range reduction (around one fourth) occurs with respect to the trimmed tuned case. As expected, the latter result justifies the need for an antenna tuning (trimming operation) of the inlay tag.

4. CONCLUSIONS

A numerical and experimental study was conducted on the use of a magneto-dielectric slab in combination with inlay tags to realize low-profile (2 mm thick) on-metal UHF RFID tags. Two common disposable UHF inlay tags, intrinsically not suitable for on-metal use, were analyzed: the Alien ALN-9640 Squiggle® Inlay and the Alien ALN-9654 G Inlay. It was shown how loading the tag antenna with a magneto-dielectric slab interposed between the tag and a metallic surface allows the tag input impedance to raise up from the very low values induced by the presence of a metal surface. Then, it was shown that some simple straight cuts of some parts of the antenna layout can be identified to tune the tag impedance in the UHF band and maximize the power transmission coefficient. Both simulation data and measurements showed that a maximum power transmission coefficient very close to unit can be achieved, for both the above commercial tags.

The proposed solution is an alternative approach to get a low-profile on-metal tag, with respect to redesign and manufacture a completely new tag antenna. It is worth noting that inlay tags and some commercial thin magnetic laminates (Emerson&Cuming Eccosorb MCS-U) are adhesive and can be easily stuck on smooth surfaces. Also, simple cuts of external parts of the antenna layout have been shown to be effective to tune the antenna input impedance. Although the method effectiveness has been shown only for a couple of commercial inlay tags, the latter are representative of a large class of inlay tags including meandered dipoles, end-loaded dipoles, and folded dipoles. Therefore, it is expected that the proposed procedure works for most of the commercial dipole-like inlay tags. Nevertheless, the same procedure could be tested with some different inlay tag classes.

REFERENCES


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Q-FACTOR IMPROVEMENT OF INTEGRATED INDUCTORS USING HIGH ASPECT RATIO FERROMAGNETIC NANOWIRES

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ABSTRACT: We fabricated a planar inductor onto a substrate made of high aspect ratio ferromagnetic nickel nanowires in a self-supported alumina nanoporous membrane. We observe a simultaneous increase of the inductance value and the quality factor up to 7 GHz, thanks to the large amount of ferromagnetic material and the nanoscale of the wires limiting conducting losses. Our device shows the largest increase reported in the literature for such ferromagnetic inductors: +30% for the inductance value and +22% for the quality factor. Even more, this technology offers great advantages as an easy integration in miniaturized topologies and its tunability to a magnetic field to broaden the desired frequency range. Our analytical model predicts that the increase of quality factor can be maximized up to 35% by an optimization of the pores filling. © 2012 Wiley Periodicals, Inc. Microwave Opt Technol Lett 54:1633–1637, 2012; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.26900

Key words: ferromagnetic nanowires; planar inductor; quality factor; microwave
1. INTRODUCTION

Arrays of ferromagnetic nanowires embedded in a nanoporous membrane, also called nanowired substrate, offer outstanding properties in the microwave range of frequencies, such as a high operation frequency, a larger saturation magnetization due to a very large aspect ratio of the nanowires, and the ability to work without any applied magnetic field. Even more, arrays of ferromagnetic nanowires in a regular nanoporous alumina (Al₂O₃) membrane present full compatibility with microlithography and nanolithography techniques used in integration of devices for systems in package or on chip. Thanks to these advantages, telecommunication applications based on nanowired substrate instead of classical ferries can be conceived. Previous works have reported the possibility to use a nanowired substrate in various microwave devices such as circulators [1], isolators [2], noise suppressors [3]... On the other hand, the microelectronics industry is in demand for compact integrated inductors with high inductance and quality factor operating up to several GHz. The first solution is to use a low-loss substrate, like bulk alumina [4] or porous silicon [5], allowing a decreasing of losses of the system. The second solution is to include a ferromagnetic core in the structure, with the important drawback that ferromagnetic resonance (FMR) losses and eddy currents induced in the volume of the core deteriorate the quality factor at RF frequencies. Various technologies were proposed in the literature to overcome those problems. First, a very thin ferromagnetic layer was placed into the core of inductor for increasing its inductance value [6], with the inconvenience that the FMR frequency is usually limited to 1 GHz [6–9]. Next, modified geometries of the ferromagnetic layer were proposed to increase the shape anisotropy field, hence the FMR frequency, and reduce simultaneously the cross-section accessible to eddy currents: slotted [7] or wire/strip patterned [8, 10] ferromagnetic films, micro/nano patterned ferromagnetic cores [9], or nanocomposite cores made of Ni-supported nanoporous alumina membrane [11]. In these topologies, the low amount of ferromagnetic material required to avoid eddy currents together with the attempt to increase the FMR frequency prevents an important increase of permeability [12], hence of the inductance. Reported values are usually lower than 15%, and the corresponding quality factor does not follow the inductance enhancement: it is kept unchanged or even lowered. In this article, both solutions are used: the combination of high porosity and thick self-supported alumina membrane enables to supply a large amount of magnetic material to maximize the value of inductance while the nanowired alumina membrane is also able to drastically limit substrate losses up to several GHz and avoid eddy currents in the ferromagnetic material, thanks to the nanoscale of wires. With high aspect-ratio ferromagnetic nickel (Ni) nanowires, we observe a simultaneous increase of inductance and quality factor up to 7 GHz. A theoretical model, which includes geometrical and material parameters and also validated by experiment, is used to optimize the enhancement of those two parameters. The porosity or the filling height of the pores has a key influence on their increase whereas the application of a DC magnetic field enables to extend the frequency range of improvement.

2. TOPOLOGY AND OPERATION

A self-supported nanoporous alumina membrane made by anodization techniques composes the template used for growing the ferromagnetic nanowires forming the nanowired substrate. Different characteristics can be controlled by these techniques or by an acid treatment of pores surface: porosity, height of membrane, and size of pores. For the devices presented in this article, we fill a commercial membrane from Whatman (Anodisc 47, series 6809-5012) with as nominal characteristics of 60 μm thickness, 35% porosity, and 100 nm pores size. A large porosity and thickness allow in having an important volume of ferromagnetic material in the membrane to enhance the FMR effect. Nanowire diameter is much smaller than the skin depth of Ni at microwaves, so that electromagnetic waves can penetrate nanowires without attenuation [13]. For this reason, we can observe FMR despite of the metallic nature of nanowires. One micrometer-thick Cu/Au layers are deposited on one side of the alumina membrane. This layer serves as a cathode electrode for the electrochemical deposition process and as ground for the inductor device. The electrodeposition method controls the filling of nanopores. In this article, we use an Al₂O₃ membrane with Ni nanowires filling in average 40% of the height of membrane. We proceed to a deposition of thin silicon oxide (SiO₂) layer (500 nm) by plasma-enhanced chemical vapor deposition on the top of nanowired Al₂O₃ membrane to avoid a possible short circuit from coplanar inductor to the ground through some over-long nanowires. Aluminum metal layer (500 nm) is deposited on the SiO₂ layer by photolithography, using a mask including various inductor geometries. The nonprotected part of aluminum is etched by chlorine plasma.

We use a vector network analyzer Model Anritsu 37369A and coplanar ground-signal-ground RF probes to measure (transmission and reflection) S-parameters of meander inductors with coplanar waveguide (CPW) connecting pads (Fig. 1) for frequencies ranging from 40 MHz to 15 GHz. A line-reflect-match calibration is done before measurements using an impedance standard substrate to remove the influence of cable losses and CPW probe contact pads. Both samples with and without nanowires are measured.
Simulations are performed using an analytical model \cite{14, 15} for frequencies from 0.5 to 15 GHz. Calculations consider the FMR of nanowires involved in the formula of relative permeability of the substrate, as explained in next section, dielectric losses of alumina membrane depending of porosity, the coupling between strips of the meander inductor, and the skin depth effect from aluminum electrodes. The actual geometrical dimensions of the meander are used for the model: width and height of strip equal to 16 μm and 500 nm, respectively, spacing between strips equal to 10 μm and total length of the meander equal to 1500 μm. Simulations calculate the S-matrix characterizing the propagation of signal between ports and its reflection at each port.

Thanks to the equivalent circuit defined on Figure 1, we can calculate Y parameters from S-matrix values, and extract all elements to show their RF dependence, as defined in Ref. 12. The inductance L and the resistance R correspond to the planar meander inductor and depend on the magnetic behavior of substrate and the ohmic losses of the meander stripline conductor, respectively. Conductances $G_{1,2}$ and capacitances $C_{1,2}$ are directly issued from the dielectric behavior of substrate and represent impedances between ground and port 1 or 2. Owing to the geometrical symmetry of planar inductor, we consider $G_1 = G_2 = G$ and $C_1 = C_2 = C$. Quality factor is found using complex impedances: $Q = 2πfL/(R + G)$. In our case, capacitance and conductance values are negligible compared, respectively, with inductance and resistance values, so that the quality factor rewrites $Q = 2πfL/R$.

3. RESULTS AND DISCUSSION

3.1. Inductance and Losses

In Figure 2, we can compare the normalized-phase (top left) of transmission parameter $S_{21}$ for meander inductor lying on Ni nanowired membrane, in experiment (solid) and simulation (dashed). These curves are normalized with respect to corresponding phase for the same inductor lying on non-nanowired substrate. Because of the large porosity of alumina membrane, remanent magnetization can be approximated as zero. FMR frequency is calculated as $f_1 = 1/2 \gamma M_s$, where $\gamma = 3.09 \text{ GHz kOe}^{-1}$ and $M_s = 485 \text{ emu cm}^{-3}$ are gyromagnetic factor and saturation magnetization, respectively \cite{16}. FMR effect is identified at 9 GHz by an inflection point in normalized-phase graph (top left), in inductance graph (top right), and in permeability graph (down right). In resistance graph (down left), FMR effect is visible through a maximum of losses observed at resonance. The relative permeability of the substrate depends on ferromagnetic nanowires embedded in alumina membrane. When no nanowires fill the membrane, relative permeability is equal to 1. In a nanowired substrate, its relative permeability depends on the relative permeability of nanowires in the low frequency range \cite{17} and on the FMR, and can be defined as a tensor:

$$\tilde{\mu} = \begin{pmatrix} \mu_{r,rows} + K & -i \eta & 0 \\ i \eta & \mu_{r,rows} + K & 0 \\ 0 & 0 & \mu_{t,rows} + K \end{pmatrix}$$

$$K = 2\pi M_s \gamma P h_m \left( f_0^2 - f^2 \right)^{-1} (m^2 + 1)$$

$$\eta = 4\pi M_s \gamma P h_m \left( f_0^2 - f^2 \right)^{-1} m$$

where $P$ is the porosity of the membrane, $h_m$ the height of nanowires, and $m = M/M_s$ the normalized magnetization. We can see in Figure 2 that the graph of inductance is quite similar to the one of relative substrate permeability. This confirms the dependence of inductance to the magnetic parameters of the substrate, that is, directly to its permeability.
In Figure 2 (down right), the relative substrate permeability is larger in the presence of ferromagnetic nanowires, over the whole measured frequency range. This increase is even larger below the FMR frequency. We can explain that by the change of sign in $K$ term [Eq. (1)] when frequency $f$ is below or above the FMR frequency $f_r$. $\Delta \mu$ is about $+30\%$ in the frequency range below $f_r$. This increase affects in the same way the value of the inductance. Indeed, simulations and measurement show that the inductor on nanowired substrate presents a larger value of inductance than inductor on non-nanowired substrate, and the maximum increase is observed in the frequency range below $f_r$ and is about $30\%$.

As announced before, the resistance (Fig. 2, down left) of inductor on nanowired substrate shows a maximum at FMR frequency, due to absorption of microwaves by ferromagnetic nanowires. Nevertheless, it is worth noticing that in low frequencies range (below $f_r$) the resistance is of the same order of magnitude ($<12\ \Omega$) for nanowired and non-nanowired substrate inductor, because conducting losses in nanowires are minimized even at microwaves due to their nanoscale.

### 3.2. Quality Factor

Consequence of this is an increase of the quality factor in the frequency range below FMR frequency. Figure 3 shows evidence of this increase for frequencies from 40 MHz to 7 GHz, reaching a maximal value of $23\%$ at 4 GHz. Simulations predict that we can have larger operation frequencies when applying a DC magnetic field on the substrate. This magnetic field is parallel to the nanowires and gives rise to a shift to larger FMR frequencies. As before, the inductance value is larger for frequencies below the FMR frequency while losses remain the same for those frequencies. For non-nanowired substrate, the DC magnetic field does not have any influence because there is no magnetic material. As a result, simulations without and with applied DC magnetic field of 4 and 6 kOe show, in Figure 3, an improvement of quality factor higher for frequencies up to 7 GHz, 9 GHz, and 14 GHz, respectively. FMR frequencies for those simulations are, respectively, 9, 12.5, and 18.5 GHz.

As mentioned previously, the fabricated device has nanowires filling in average $40\%$ of alumina membrane, yielding an increase of quality factor of about $23\%$ at 4 GHz. We can improve this value by increasing the amount of ferromagnetic material in $Al_2O_3$ membrane. The filling of membrane nanowires can go until $100\%$. In this ideal case, as we see in Figure 4, the enhancement of quality factor can reach $35\%$.

Different strategies offer to optimize the Q-factor. We can increase the porosity of the membrane to increase the presence of ferromagnetic material. Losses can also be minimized via the increase of the thickness of electrodes, up to the minimal skin depth value over considered frequency range (i.e., $1.45\ \mu m$ at 4 GHz for aluminum with conductivity of $3 \times 10^7$ S/m). Geometrical optimization of inductor at fixed length (spiral instead of meander) could also increase the inductance value, without increasing the resistance of the system. It could optimize the quality factor.

### 4. CONCLUSIONS

In conclusion, we fabricated a planar integrated inductor on a Ni-nanowired substrate that improves simultaneously inductance and quality factor values up to 7 GHz. An analytical model, validated by experiment, predicts the enlargement of operating frequency range by applying a DC magnetic field, and that adjusting nanowires height and geometry of metallic conductor forming the inductor can maximize this increase.

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1. INTRODUCTION

Optical high frequency for wireless communication has been widely used in several ways such as radio frequency identification (RFID). In RFID communication system, the information is normally exchanged between readers and tags. The information typically stored in a tag is for the purpose of identification. Moreover, RFID applications of interest include book identification in a library system, animal identification in livestock management, control for transportation systems and it is a common term used for technology that uses radio waves to identify objects or people. Many research works have been concentrated about on the surface technology that uses radio waves to identify objects or people.

2. THz FREQUENCY GENERATION

Light from a monochromatic light source is launched into a ring resonator with constant light field amplitude ($E_0$) and random phase modulation as shown in Figure 1, which is the combination of terms in attenuation ($a$) and phase ($\phi$) constants, which results in temporal coherence degradation. Hence, the time-dependent input light field ($E_{in}$), without pumping term, can be expressed as [17].

$$E_{in}(t) = E_0 e^{-a t / 2} e^{j \phi(t)}$$

Here $L$ is a propagation distance (waveguide length).

We assume that the nonlinearity of the optical ring resonator is of the Kerr type, i.e., the refractive index is given by:

$$n = n_0 + n_2 I = n_0 + n_2 \left( \frac{P}{A_{eff}} \right)$$