On-chip artificial magnon-polariton device for voltage control of electromagnetically induced transparency

Sandeep Kaur1, Bimu Yao1,2, Yong-Sheng Gui1 and Can-Ming Hu1

1 Department of Physics and Astronomy, University of Manitoba, Winnipeg, R3T 2N2, Canada
2 National Laboratory for Infrared Physics, Chinese Academy of Sciences, Shanghai 200083, People’s Republic of China

E-mail: kaurs3@myumanitoba.ca

Received 16 August 2016, revised 3 October 2016
Accepted for publication 10 October 2016
Published 1 November 2016

Abstract
We demonstrate an on-chip device utilizing the concept of an artificial cavity magnon-polariton (CMP) generated via coupling between a microwave cavity mode and the artificial magnetism dynamics of a split ring resonator. This on-chip device allows the easy tuning of the artificial CMP gap by using a DC voltage signal, which enables tuneable electromagnetically induced transparency. The high tunability of the artificial magnon-polariton system not only enables the study of phenomena associated with the classical analogues of different coupling regimes, but also may open up avenues for designing advanced microwave devices and ultra-sensitive sensors.

Keywords: metamaterials, electronic circuits, polaritons

(Some figures may appear in colour only in the online journal)

1. Introduction

When an electromagnetic wave propagates in a magnetic material, its magnetic fields can drive magnetization precession and the mutual coupling between the macroscopic electrodynamics and magnetization dynamics results in a hybrid electromagnetic mode of the media, i.e. magnon polariton [1]. In light of this principle, a cavity magnon polariton (CMP) has been recently studied in a coupled magnon-cavity photon system [2], where the general feature of the CMP can be described in a concise classical model [2] which accurately highlights the key physics of phase correlation between the cavity and magnetization resonances. This general CMP model can be used to quantitatively analyze the characteristic features of magnon–photon coupling experiments recently performed by many different groups [2–11], in which a low damping bulk ferromagnetic insulator is set either on-top of a superconducting co-planar waveguide or inside a high quality 3D microwave cavity.

The intriguing physics of CMP opens up new avenues for materials characterization and microwave applications. For example, the CMP effect has recently been observed by setting miligrams of magnetic nano-particles inside a special circular waveguide cavity [12], where the CMP coupling can be analyzed in the simple 1D configuration by using either the straightforward transfer matrix method [12], or equivalently, the 1D scattering theory [13]. It is found that the CMP coupling enables quantification of the complex permeability of magnetic nanoparticles with high sensitivity, which was an outstanding challenge for biomedical applications of magnetic nanoparticles [12]. In 3D microwave cavities, it has been shown that the CMP coupling leads to the electromagnetically induced transparency (EIT), which is tuneable by applying an external magnetic field [5]. Such a tuneable EIT is of great importance for designing microwave circuits.

The EIT effect was first found as being a quantum interference effect that permits the propagation of light through an otherwise opaque atomic medium [14]. With the advancement of EIT physics as well as the metamaterial media design, EIT behavior was observed in metamaterial analogue systems due to interference between coupled classical resonators, which gives rise to opportunities for studying narrow-band
transmission and light-slowing effects at room-temperature [15–22]. Moreover, the EIT effect generated from the CMP coupling allows us to study the energy exchange between confined photons and spin precession. By studying this effect, a cavity spin pumping method which uses both spintronics and quantum information has recently been developed and can be used to coherently manipulate spin currents and develop quantum transducers that can consistently link different quantum systems. Control of the energy exchange between the photon-magnon mode is essential for the development of these applications. Therefore, it is important to develop a CMP system whose mode evolution and coupling strength can be easily tuned, and also has the advantages of having a relatively easy control of energy exchange rate, room temperature operation and easy integration with a microwave circuit.

From the perspective of device application the external magnetic field used to alter the energy exchange efficiency between a photon and a magnon in a CMP system is not favourable. Inspired by the study of artificial magnetism [23, 24], where the non-magnetic conducting material is designed to provide a magnetic response at microwave frequencies, in this paper, we report on a 2D artificial CMP system created by integrating an artificial magnetic resonator with an on-chip cavity resonator. Here the cavity mode and the artificial magnon mode are generated by a cut wire resonator connected to a transmission line and a varactor loaded split ring resonator mutually coupled with the cut wire respectively. The microwave magnetic field radiated by the cut wire resonator induces a microwave current in the split ring resonator and thus produces an effective magnetic response, which can be characterized by the resonant permeability of the structure [23]. By altering the DC voltage bias of the varactor diode, the resonance frequency of the split ring resonator can be varied in a wide range. Aligning the resonance frequency of the photon and the pseudo-magnon subsystem, the artificial CMP gap induced by electrodynamic coupling is observed, creating tunable EIT using a DC voltage. To explain the experimental observations, we have developed a coupled LCR circuit model, where the coupling strength is determined by the mutual inductance and is proportional to the distance between the two structures based on Biot Savart’s law. Devices based on this 2D artificial CMP may provide new platforms to study the coupled photon-quasi-particle system, allowing the on-chip observation of phenomena associated with the classical analogues of different coupling regimes including weak coupling, strong coupling, EIT and Purcell effect, all controlled by a DC voltage.

2. Transmission line model

Similar to that of the CMP [2], the dispersion of the artificial CMP can be completely described by five parameters: the resonance frequency of the cavity mode (ωc), the resonance frequency of the pseudo-magnon mode (ωs), the damping factor of the cavity mode (ωc), the damping factor of the pseudo-magnon mode (ωs) and the coupling strength (κ) between the two modes. To quantify them from the observed microwave response of the artificial CMP the transmission line theory of the coupled LCR circuit is developed which describes wave propagation in terms of current, voltage and impedance [25].

We first used the transmission model described in [26] to characterize the LCR parameter in the individual cut wire resonator and split ring resonator. As shown in the inset of figures 1(a) and (c) the cut wire resonator and the split ring resonator can be treated as LCR circuits with impedances

![Figure 1](image-url). Experimentally measured (symbols) and analytically calculated (solid lines) transmission curves for (a) the cut wire resonator connected to a 50 Ω transmission line, (c) the split ring resonator excited by a 150 Ω transmission line, and (e) the coupled cut wire and split ring resonator separated by a distance of 2.7 mm. The insets show the corresponding equivalent LCR circuits and (b), (d) and (f) are photographs of the fabricated microwave devices.
\[ Z_c = R_c + i(\omega L_c - 1/\omega C_c), \]  
\[ Z_s = \omega L_s - R_s \omega^2 L_s C_s \frac{1}{1 - \omega^2 L_s C_s + i\omega C_R R_s}, \]

where the subscripts ‘c’ and ‘s’ denote the parameter for the cut wire resonator and the split ring resonator respectively, and \( \omega/2\pi \) is the microwave frequency. Note that the LCR circuit for the split ring resonator shown in figure 1(c) can also be equivalently represented as a capacitor parallel to an inductance in series with a resistor. For this case, the impedance is given by \( Z'_s = \frac{R'_s + j\omega L'_s}{1 - \omega^2 L'_s C'_s + j\omega C'_s R'_s} \). The values of \( R'_s \) and \( C'_s \) will be slightly different than \( R_s \) and \( C_s \) nonetheless, the response of the two circuits will be the same which implies that the two representations can be used interchangeably. Through the transfer matrix [25] the related transmission coefficient \( S_{21} \) parameter can be easily obtained as

\[ S_{21} = 2Z_i/(2Z_c + Z_0), \]  
\[ S_{22} = 2Z_0/(2Z_c + Z_0), \]

for the cut wire resonator and the split ring resonator respectively, where \( Z_0 \) is the characteristic impedance of the transmission line.

When combining the two resonators to observe the artificial CMP, the LCR circuit shown in the inset of figure 1(e) can be represented as described by mutual inductance \( M \). This interaction may also be described using a transformer that links the magnetic flux generated by the cut wire resonator with the inductor of the split ring resonator. After using the net impedance of the circuit, the \( S_{21} \) parameter can be written as

\[ S_{21} = 1 - \frac{Z_0}{Z_0 + 2R_c \Delta \omega^2} \frac{\Delta \omega}{i(\omega - \omega_c) + \Delta \omega}, \]

where \( \omega_c = 1/\sqrt{L_c C_c}, \omega_c = 1/\sqrt{L_s C_s}, \Delta \omega_c = \frac{C \omega^2 (R_c + Z_0/2)}{\omega^2 + \omega_c^2}, \) and \( \Delta \omega = \frac{C \omega^2}{\omega^2 + \omega_c^2} \). The coupling strength \( \kappa = \omega^2 M \omega \Delta \omega \times \sqrt{C_c L_c (\omega^2 + \omega_c^2)} \) is linearly dependent on the mutual inductance \( M \). In the vicinity of the polariton gap which occurs at the condition of \( \omega \sim \omega_c \sim \omega_c \), it can be found that \( \Delta \omega_c \sim (R_c + Z_0/2)/2L_c, \Delta \omega_s \sim R_s/2L_s, \) and \( \Delta \omega \sim M \omega_c /2L_c L_s \). Here we only focus on qualitatively modelling the response of the coupled cut wire and split ring resonators. Thus, for simplicity purposes, we have neglected the impedance mismatch between the 50 Ω microstrip line and the 150 Ω split ring resonator lines. Notice that equation (5) has a similar form as that for the CMP due to coupling between photon and magnon, indicating the similar physical origin of the artificial CMP [2].

In order to validate this coupling model based on the transmission line theory, the cut wire resonator, the split ring resonator, and their combination shown in figures 1(b), (d) and (f) were fabricated on 1.55 mm thick FR4 substrate. The copper thickness is 35 µm. The cut wire resonator is positioned at the center of a 50 Ω microstrip line, the length and width of cut wire is 15.1 mm and 0.2 mm, respectively. The dimension of split ring resonator is 4 mm in width and 12 mm in length with a linewidth of 0.2 mm. Along the width of the split ring resonator, a 0.2 mm gap is located in the center and a 0.2 mm wide 150 Ω transmission line is used to excite the resonance. In figure 1(f) the separation between the center of the two resonator structures is 2.7 mm and the microstrip line has a characteristic impedance of 50 Ω. The transmission parameter of these fabricated devices was then measured using a vector network analyzer.

The experimentally measured transmission curves are shown in figures 1(a), (c) and (e) respectively where a transmission minimum is observed at the resonance frequency of 3.0 GHz in the spectrum for both the resonators whereas a transmission maximum centred at the resonance frequency of 3.0 GHz is obtained when the two resonators are coupled.

By fitting the experimental transmission curves for the cut wire and the split ring resonators using our transmission line models equations (3) and (4), the transmission curves obtained are displayed in figures 1(a) and (c) respectively. The corresponding values of \( R_c = 2.87 \) Ω, \( C_c = 0.499 \) pF and \( L_c = 5.64 \) nH for the cut wire resonator, and \( R_s = 0.091 \) Ω, \( C_s = 8.78 \) pF and \( L_s = 0.314 \) nH for the split ring resonator were obtained from the fitting. Then the measured transmission spectrum corresponding to the coupled resonator (shown in figure 1(c)) was calculated with just one fitting parameter i.e. mutual inductance (\( M = 0.74 \) nH).

3. Experimental results

Since the mutual inductance \( M \) determines the coupling \( \kappa \), which characterizes the energy transfer efficiency from the cavity system to the quasi-particle system [2], it is necessary to understand its physical origin in an artificial CMP for microwave applications. In the second experiment, the distance between two resonators fabricated as different chips was changed in the horizontal direction using an x-y-z stage. Figure 2 shows the schematic diagram of the experimental setup used where the cut wire resonator shown was directly connected to the vector network analyzer whereas the split ring resonator was mounted on the x-y-z stage and the separation between the two chips was less than 20 µm.

3.1. Distance dependence of coupling

The left panel of figure 3(a) shows some typical \( S_{21} \) spectra obtained at different values of distance \( y \) between the cut wire resonator and the center of the split ring resonator, and the right panel shows the corresponding amount of magnetic flux passing through the split ring resonator. From figure 3(a) it can be easily seen that as the distance \( y \) decreases, the magnetic flux increases which corresponds to an increase in the coupling strength \( \kappa \). Due to this increased coupling strength, the transmission window increases and reaches a maximum when both resonators are close without any overlap. However, when the cut wire resonator is exactly at the centre of the split
Figure 2. Schematic diagram of the experimental setup used to achieve active tunability of the coupling associated with our artificial CMP system. The 50 Ω transmission line integrated with a cut wire resonator in the center is directly connected to the vector network analyzer whereas the split ring resonator chip is mounted on the x-y-z stage which is used to tune the distance between the two resonators.

ring resonator (y = 0), the net magnetic flux is zero due to the cancellation. Hence, the transmission window vanishes at the centre but reappears as soon as the centres of the two resonators are no longer aligned. Figure 3(b) shows the transmission amplitude mapping result obtained by tuning the distance y in the horizontal direction.

Based on the amplitude mapping result obtained in the previous section, a relationship between the mutual inductance $M$ and the distance y can be established and the result is shown in figure 4(a), which can be theoretically explained by determining the magnetic flux ($\phi$) through the split ring resonator due to the induced current (I) flowing in the cut wire resonator, given by

$$M = \frac{\phi}{I} = \frac{\oint B \cdot dA}{I},$$

where $B$ is the microwave magnetic field produced by the cut wire resonator and $A$ is the area of the split ring resonator. For simplicity by neglecting the contribution caused by the substrate here we integrate the magnetic field over the width of the split ring resonator and simply multiply with its length. The result is shown in figure 4(a) where good qualitative agreement is observed between the experimental result and the theoretical expectation.

We note that different coupling regimes can be characterized by the relative coupling strength of $\kappa/\Delta\omega_2$ and $\kappa/\Delta\omega_3$ according to equation (5), which reflects the energy exchange between the photon and pseudo-magnon sub-systems and the energy dissipation in them. At $\kappa/2\pi = 0.017$ GHz, $\Delta\omega_2/2\pi = 0.3$ GHz and $\Delta\omega_3/2\pi = 1$ MHz, the $S_{21}$ spectra in figure 4(b) shows a narrow transmission window centred at the resonance frequency, which is similar to the EIT originally observed in three level systems of atomic gases [27] due to destructive interference between two different excitation pathways [28]. The two different excitation pathways are often labelled as the bright and the dark mode and respectively correspond to the mode that can and cannot be directly excited by the incident radiation [15]. In the artificial CMP system presented here, the cut wire which acts as a photon system is the bright mode since its resonance can be directly excited by the incident microwave radiation. Where as, the split ring resonator that acts as a pseudo magnon system represents the dark mode that can only be excited through coupling to the bright mode. The parameters of the classical transmission line analog of EIT can also be related to the atomic system. For example, the resonance frequencies of the photon and the pseudo magnon mode $\omega_p = \frac{1}{\sqrt{LC_p}} = 3.03$ GHz, $\omega_d = \frac{1}{\sqrt{LC_d}} = 3.0$ GHz correspond to the Rabi represented frequencies of bright and dark mode transitions respectively whereas the relaxation time of the system can be calculated as $t = R/L_s = 29 \mu s$.

Researchers have already realized that the essential physics behind EIT in analogous systems can be described classically, and similar behavior can be observed in very simple systems, such as metamaterials [19, 20, 22, 29–31]. However, in the artificial CMP system not only the coupling strength $\kappa$ but also the damping parameters can be effectively tuned by integrating resistors [21, 33, 34]. Therefore, these systems can be used to observe the classical analogues of different coupling regimes i.e. strong ($\kappa > \Delta\omega_2, \Delta\omega_3$), weak ($\kappa < \Delta\omega_2, \Delta\omega_3$), EIT ($\Delta\omega < \kappa < \Delta\omega_2$) and Purcell ($\Delta\omega_2 < \kappa < \Delta\omega_3$) range [5]. The typical transmission curve obtained (using equation (5)) for the respective coupling regimes are shown in figures 4(c)–(e).

3.2. Voltage control of metamaterial EIT

High tunability of the artificial CMP system allows the fabrication of an on-chip microwave device, demonstrating the capability of the voltage control of EIT. Based on the dependence of mutual inductance on the distance between two resonators, the appropriate coupling region ($\Delta\omega_2 < \kappa < \Delta\omega_3$) was chosen to demonstrate this active voltage control of the transparency window associated with EIT, where the artificial CMP gap is generated by electrodynamic coupling. In the device a varactor diode (Skyworks SMV 2019) was soldered onto the split ring resonator which had a capacitance tuning range from 2.2 pF to 0.3 pF [32] as shown in the schematic diagram figure 5(a). Two r-f chokes were soldered at the two edges of the split ring resonator, on either side of the varactor diode to decouple the DC current applied to the diode and the high frequency microwave current induced in the split ring resonator. The DC voltage was then applied across the edge of the split ring resonator which contains the diode. As the applied DC voltage bias is tuned, the resonance frequency $\omega_2$ of the varactor-loaded split ring resonator will change while the resonance frequency $\omega_3$ of the cut wire resonator remains constant at 3 GHz.

In the device configuration shown in figure 5(a), both resonances have been observed even at conditions of $\omega_2 = \omega_3$ due to the mutual coupling between the photon and pseudo-magnon subsystem. As shown in the typical $S_{21}$ spectra in figure 5(b) the amplitude of the resonance of the split ring resonator is an order of magnitude weaker compared with that of the cut
wire resonator when $\omega_s$ is far from $\omega_c$, indicating the less-effective efficiency of the energy transfer from the cut wire resonator to the split ring resonator. The transmission at the resonance of the split ring resonator is significantly enhanced when $\omega_s$ approaches $\omega_c$ due to the generation of artificial CMP.

A general phenomenon known as ‘avoided level crossing’ occurs when the two subsystems have identical resonance, i.e. $\omega_s/2\pi \approx \omega_c/2\pi \approx 3.0$ GHz at the applied voltage of about 6.5 V,
where the photon-like and the pseudo-magnon-like polariton have equal amplitude and neither of them occurs at 3.0 GHz. As a result the polariton gap (about 0.3 GHz) of the artificial CMP is observed, creating EIT near 3 GHz.

Figure 5(c) shows the measured dispersion of an artificial CMP in a voltage-controlled microwave device, where the hybridization of the pseudo-magnon and cavity modes is clearly seen, generating the photo-like and pseudo-magnon-like polaritons separated by a gap near 3.0 GHz. As the applied voltage increases, the device changes from being partially transparent to completely transparent and then to being completely opaque at about 3.0 GHz. In a coherent coupling system consisting of a magnon mode and a microwave cavity mode, CMP is generated when the magnon mode approaches the cavity mode. When the dissipation of the microwave cavity mode becomes dominant in the coupled system, a transparency window in the transmission similar to the classical EIT can be observed which can be tuned by tuning the external magnetic field [5]. In contrast to CMP systems where a magnetic field is used to tune the resonance frequency of the magnon modes, in this artificial CMP system we use the applied voltage to tune the frequency of the pseudo-magnon mode. The voltage control of the resonance frequency of the varactor loaded split ring resonator, controls the efficiency of energy transfer between the cavity mode and the pseudo magnon mode. By tuning the voltage bias, the resonance frequency of the two modes is matched. Dominated by the dissipation of the cavity mode, there is efficient energy transfer between the two modes which creates EIT like profile in this structured system.

One can calculate the dispersion of an artificial CMP based on equation (5) by integrating the equivalent circuit of the varactor diode, which includes multiple electronic elements. Here we highlight the electrically tunable feature of this hybrid device by assuming that only the capacitance varies with the applied DC voltage. Assuming \( C_r \) of the varactor is in series connection with \( C_z = 2.7 \text{ pF} \) for a split ring resonator with \( L_s = 0.88 \text{ nH} \), the \( S_{21} \) spectra is calculated as shown in figure 5(d), qualitatively reproducing the observed EIT feature in the coupled photon-pseudo-magnon system. The quantitative differences between figures 5(c) and (d) can be attributed to the effect of impedance mismatch between the microstrip line and the split ring resonator line, or to the simplicity of the circuit used for the varactor diode and a saturation of the capacitance of the varactor diode at higher voltages, or to a combination of these two effects. Note that while varactor loaded microstrip resonators have been studied in the past [35, 36], in this work we use the varactor to tune the resonant response of the split ring resonator which tunes the response of the whole device due to mutual coupling. Therefore, by using a varactor loaded split ring resonator, voltage tunable EIT can be achieved. Furthermore, even though tunable EIT has been achieved by the CMP controlled by a static magnetic field, the artificial CMP is an on-chip device controlled by the DC voltage and thus is more convenient for practical applications.

4. Conclusion

In summary, by introducing the concept of artificial CMP, an on-chip hybrid device has been fabricated, where the artificial CMP gap induced by electrodynamic coupling is demonstrated, achieving voltage-tunable electrodynamically induced transparency in the microwave range. A transmission line model which describes the electrodynamic coupling between the cavity and the pseudo-magnon mode has been developed. Our 2D system has demonstrated high tunability, allowing the observation and evaluation of characteristic phenomena associated with the classical analogues of distinct

Figure 5. (a) Schematic diagram of the artificial CMP device with a distance of about 4 mm between the two resonators. (b) Typical \( S_{21} \) spectra (offset for clarity) obtained at different values of applied voltage. At about 3.0 GHz, the device changes from being transparent to opaque as the voltage is changed. (c) Measured and (d) calculated transmission amplitude of artificial CMP formed by using a varactor diode biased by DC voltage signals.
coupling regimes. This system could also be potentially used for fabricating dynamic filters and to switch devices.

Acknowledgments

This work has been funded by NSERC, CFI, MGS, the Science and Technology Commission of Shanghai Municipality (STCSM No. 16ZR1445400), and the National Natural Science Foundation of China Grant No. 11429401. We would like to thank L. H Bai, B W Southern, J Dietrich, G E Bridges and L Fu for discussions.

References

[1] Mills D L and Burstein E 1974 Polaritons: the electromagnetic modes of media Rep. Prog. Phys. 37 817–926
[2] Bai L, Harder M, Chen Y P, Fan X, Xiao J Q and Hu C-M 2015 Spin pumping in electrodynamiсally coupled magnon-photon systems Phys. Rev. Lett. 114 227201
[3] Huebl H, Zollitsch C W, Lotze J, Hocke F, Greifenstein M, Marx A, Gross K and Goennenwein S T B 2013 High cooperativity in coupled microwave resonator ferrimagnetic insulator hybrids Phys. Rev. Lett. 111 127203
[4] Tabuchi Y, Ishino S, Ishikawa T, Yamazaki R, Usami K and Nakamura Y 2014 Hybridizing ferromagnetic magnons and microwave photons in the quantum limit Phys. Rev. Lett. 113 083603
[5] Zhang X, Zou C-L, Jiang L and Tang H X 2014 Strongly coupled magnon and cavity microwave photons Phys. Rev. Lett. 113 156401
[6] Goryachev M, Farr W G, Creedy D L, Fan Y, Kostylev M and Tobar M E 2014 High cooperativity cavity QED with magnons at microwave frequencies Phys. Rev. Appl. 2 050402
[7] Haigh J A, Lambert N J, Doherty A C and Ferguson A J 2015 Dispersive readout of ferromagnetic resonance for strongly coupled magnons and microwave photons Phys. Rev. B 91 104410
[8] Lambert N J, Haigh J A and Ferguson A J 2015 Identification of spin wave modes in yttrium iron garnet strongly coupled to a co-axial cavity J. Appl. Phys. 17 053910
[9] Abdurakhimov L V, Bunkov Yu M and Konstantinov D 2015 Normal mode splitting in coupled system of hybridized nuclear magnons and microwave photons Phys. Rev. Lett. 114 226402
[10] Zhang X F, Zou C L, Zou N, Marquardt F, Jiang L and Tang H X 2015 Magnon dark modes and gradient memory Nat. Commun. 6 8914
[11] Zhang X F, Zou C L, Jiang L and Tang H X 2016 Superstrong coupling of thin film magnetostatic waves with microwave cavity J. Appl. Phys. 119 023905
[12] Yao B M, Gui Y S, Worden M, Hegmann T, Xing M, Chen X S, Lu W, Wroczynszyk Y, van Lierop J and Hu C-M 2015 Quantifying the complex permittivity and permeability of magnetic nanoparticles Appl. Phys. Lett. 106 142406
[13] Cao Y, Yan P, Huebl H, Goennenwein S T B and Bauer G E W 2015 Exchange magnon polaritons in microwave cavities Phys. Rev. B 91 094423
[14] Liu C, Dutton Z, Behroozi C H and Hau L V 2001 Observation of coherent optical information storage in an atomic medium using halted light pulses Nature 409 490
[15] Zhang S, Genov D A, Wang Y, Liu M and Zhang X 2008 Plasmon induced transparency in metamaterials Phys. Rev. Lett. 101 047401
[16] Dong Z G, Ni P G, Zhu J and Zhang X 2012 Transparency window for the absorptive dipole resonance in a symmetry-reduced grating structure Opt. Express 20 7206
[17] Dong Z G, Liu H, Xu M X, Li T, Wang S M, Cao J X, Zhu S N and Zhang X 2010 Role of asymmetric environment on the dark mode excitation in metamaterial analogue of electromagnetically-induced transparency Opt. Express 18 22412
[18] Papasimakis N, Fedotov V A, Zheludev N I and Prosvirnin S L 2008 Metamaterial analog of electromagnetically induced transparency Phys. Rev. Lett. 101 253903
[19] Papasimakis N and Zheludev N I 2009 Metamaterial induced transparency sharp fano resonances and slow light Opt. Photonics News 20 22
[20] Fedotov V A, Rose M, Prosvirnin S L, Papasimakis N and Zheludev N I 2007 Sharp trapped mode resonances in planar metamaterials with a broken structural symmetry Phys. Rev. Lett. 99 147401
[21] Tassin P, Zhang L, Koschmy Th, Economou E N and Soukoulis C M 2009 Low loss metamaterials based on classical electromagnetically induced transparency Phys. Rev. Lett. 102 053901
[22] Liu N, Weiss T, Mesch M, Langguth L, Eigenthaler U, Hirscher M, Sonnichsen C and Giessen H 2009 Planar metamaterial analogue of electromagnetically induced transparency for plasmonic sensing Nano Lett. 10 1103
[23] Pendry J B, Holden A J, Robbins D J and Stewart W J 1999 Magnetism from conductors and enhanced nonlinear phenomenon IEEE Trans. Microw. Theory Tech. 47 2075
[24] Smith D R, Pendry J B and Wiltshire M C K 2004 Metamaterials and negative refractive index Science 305 788
[25] Pozar D M 2005 Microwave Engineering 3rd edn (New York: Wiley) ch 4
[26] Fu L, Schweizer S, Guo H, Liu N and Giessen H 2007 Analysis of metamaterials using transmission line models Appl. Phys. B 86 325
[27] Hau L V, Harris S E, Dutton Z and Behroozi C H 1999 Light speed reduction to 17 metres per second in an ultracold atomic gas Nature 397 594
[28] Harris S E, Field J E and Imamoglu A 1999 Non linear optical processes using electromagnetically induced transparency Phys. Rev. Lett. 83 1107
[29] Liu Y and Zhang X 2011 Metamaterials: a new frontier of science and technology Chem. Soc. Rev. 40 2494
[30] Wang B Y, Liu T-C, Shen J Q and Su S-F 2015 Resonant microstrip lines analog to electromagnetically induced transparency PIERs Proc. Prague pp 1842–6
[31] Chen X, Leng X M, Li J X, Yeh Y-T, Liau T-C, Shen J Q, Kao Y H and Yang T J 2012 Experimental verification of circuit analog of three and four level electromagnetically induced transparency Adv. Mater. Res. 415–7 1340
[32] Skyworks Solution Inc 2015 Data Sheet SMV 2019 to SMV 2023 Series: Hyper abrupt Junction Tuning Varactors, Boston, USA (http://www.skyworksinc.com/uploads/documents/SMV2019_to_SMV2023_Series_200074Q.pdf)
[33] Zhang S, Zhou J, Park Y S, Rho J, Singh R, Nam S, Azad A K, Chen H T, Yin X, Taylor A J and Zhang X 2012 Photoinduced handedness switching in terahertz chiral molecules Nat. Commun. 3 942
[34] Sun Y, Tan W, Li H Q, Li J and Chen H 2014 Experimental demonstration of a coherent perfect absorber with PT phase transition Phys. Rev. Lett. 112 143903
[35] Wang Z P, Hall P S, Kelly J and Gardner P 2013 Microstrip tunable bandpass filter with the colinear resonators Int. J. Antennas Propag. 2013 960138
[36] Kapilevich B and Lukjanets R 1999 Optimization of varactor tunable microstrip resonators for wireless applications Proc. IEEE Rusia Conf. MIA-ME ’99 pp 160–7