# Magnification of subwavelength field distributions at microwave frequencies using a wire medium slab operating in the canalization regime

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Authors demonstrate numerically the magnification of subwavelength field pattern using a wire medium slab operating in the canalization regime. The magnifying slab is implemented by radially enlarging the distance between adjacent wires, and the operational frequency is tuned to coincide with the Fabry-Pérot resonance condition. The near-field pattern of a complex-shaped source is canalized over an electrical distance corresponding roughly to three wavelengths (3λ), and the pattern details are magnified by a factor of 3. The performance is also studied at several frequencies deviating from the one of the Fabry-Pérot resonance. © *2007 American Institute of Physics*.
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Canalization of subwavelength images using electromagnetic crystals was proposed by Belov *et al.*[1] Later, two experiments were carried out to demonstrate the canalization of TE-polarized (transverse electric field with respect to the slab interface)[2] and TM-polarized (transverse magnetic field) waves[3] at microwave frequencies. The slab used in the former experiment was made of capacitively loaded wires aligned parallel to the slab interfaces, whereas in the latter experiment, an array of unloaded wires aligned perpendicularly to the slab interfaces was used. The slab considered in Ref. 3 utilizes the so called "canalization regime" relying on wire-medium transverse electromagnetic modes[4,5] (TEM), allowing for transmission of the source pattern across the slab. Recently, some limitations of subwavelength imaging using such composite slabs were analytically studied in Ref. 6, and experiments aimed to verify these analytical findings are available in Ref. 7.

Following the initial studies conducted at microwave frequencies, the canalization regime was proposed to be implemented in the terahertz range using stacks of uniaxially positioned alternating dielectric layers by Belov and Hao.[8]

Recently, there has been a growing interest in developing structures that are able to *magnify* subwavelength field distributions in the visible range.[9–12] This means that the details of the source pattern are retained while transferring the image over a certain distance, and at the same time the pattern is linearly magnified or enlarged. Essentially, the structures used to demonstrate such an effect in the visible are based on stacks of two different alternating dielectric layers arranged uniaxially in Cartesian or cylindrical geometries, and one of the layers is implemented as a sheet of plasmonic metal (see also Ref. 8). In the microwave regime, simultaneous enhancement and magnification of evanescent field pattern was demonstrated experimentally with the help of double cylindrical polariton-resonant structures by Alitalo *et al.*[13]

In this letter, we demonstrate with full-wave simulations the magnification phenomenon of subwavelength field distributions at microwave frequencies using a modified version of the structure considered in Refs. 3 and 7. The proposed magnifying slab utilizes the canalization phenomenon; thus, it is capable of magnifying field pattern comprising any TM-polarized incident wave (propagating or evanescent) with any transverse component of the wave vector.[1]

A schematic illustration of the proposed slab is depicted in Fig. 1. The slab consists of metal wires (assumed in the simulations to be perfect electric conductors) whose separation is radially enlarged. The wire endings corresponding to the source interface (input interface of the slab) form a sector on spherical surface with 500 mm radius, and the wire endings corresponding to the canalized field interface (the output interface of the slab) form a corresponding sector on spherical surface with 1500 mm radius. The slab is assembled as an array of $21\times21$ wires, with the lattice period being $a=10$ mm at the input interface.

When the operational frequency (for a fixed slab thickness) is tuned to the Fabry-Pérot resonance (corresponding to

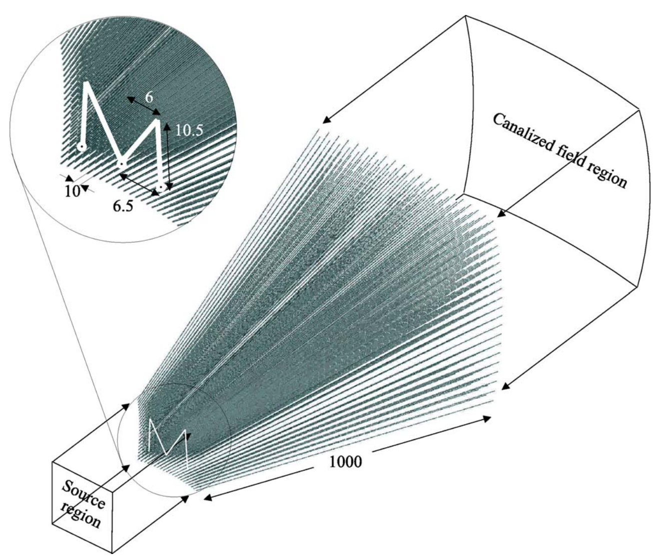


FIG. 1. (Color online) Schematic illustration of the proposed magnifying slab (all dimensions are in millimeters). Wire radius is $r_0=1$ mm. White letter *M* denotes the wire used as the source. The feed locations (current sources) are depicted as the black dots in the inset.

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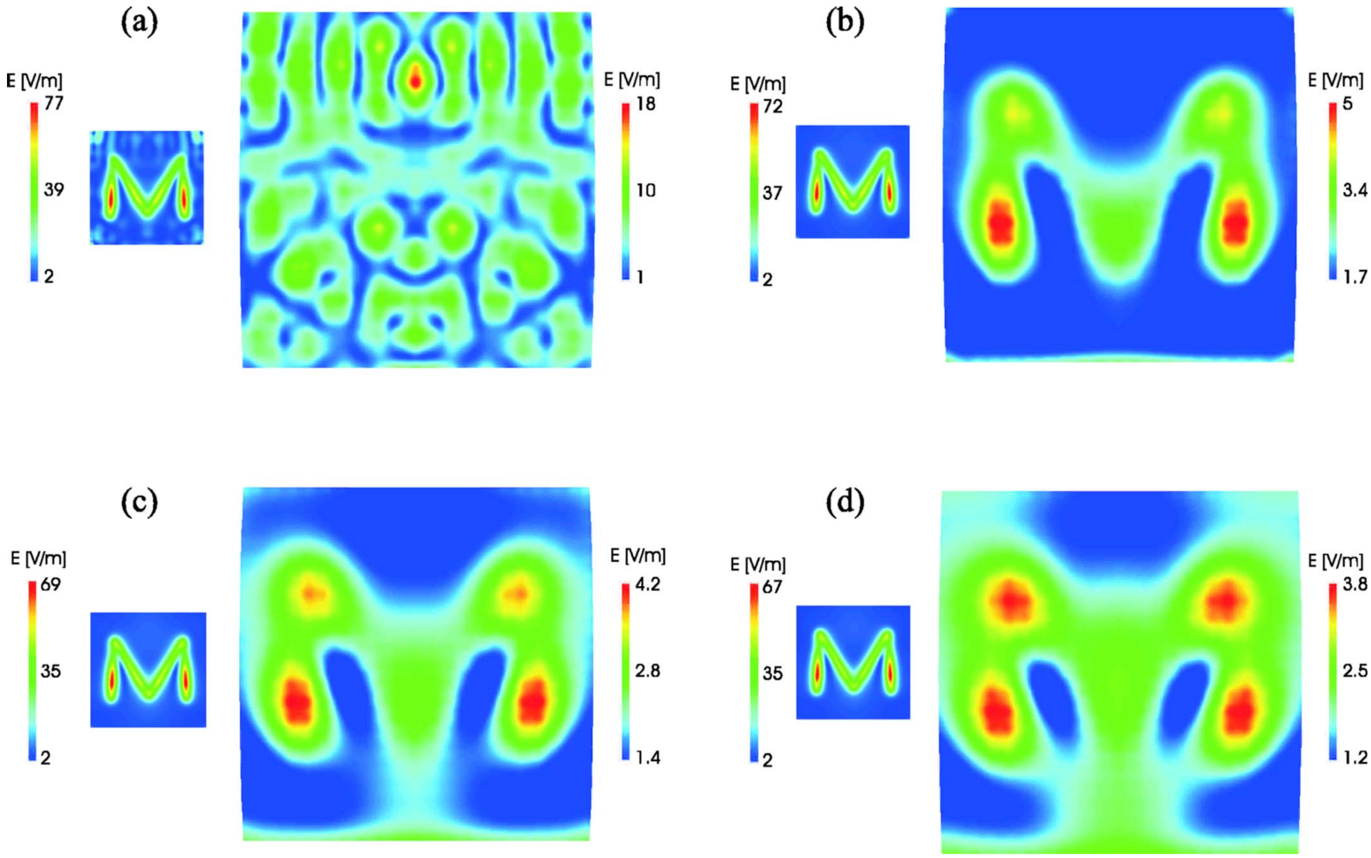


FIG. 2. (Color online) Simulated field distributions at different frequencies. (a) $f=900$ MHz, (b) $f=910$ MHz, (c) $f=920$ MHz, and (d) $f=930$ MHz. Relative sizes of the source distribution and the canalized-field distribution are in scale.

the slab thickness), the source field distortion due to reflections from the input interface is minimized, and the pattern details are transferred across the slab with the help of the wire-medium TEM modes. Note that in theory, the Fabry-Pérot resonance condition holds for any (including complex) incidence angle.[3] When the Fabry-Pérot resonance condition is met, there is no need to maintain a uniform transmission-line characteristic impedance (e.g., by altering the radius of wires), and this would ease significantly a practical implementation of the slab.

The simulations described below were performed using a commercial method-of-moments solver FEKO. The source is assumed to be a piece of wire in the shape of the letter *M* (magnification), and it is fed by three current sources. The distance between the planar source-wire plane and the wire end located in the middle of the slab input interface is 13 mm. The source field distribution is scanned over a planar surface that covers the slab input interface, and is located at a distance 8 mm behind the source-wire plane. The canalized field distribution is scanned over a spherical surface that covers the slab output interface, and is located at a 15 mm distance behind the output interface. The two scanned regions are in the following referred to as the "source region" and "canalized field region," respectively, and they are schematically depicted in Fig. 1.

Since the average distance between the source *M* and the input interface is rather small compared to the curvature radius of the interfaces, one can neglect the difference between a flat input interface and its concave analog. Indeed, in the case outlined above, the field distortion in the source region caused by uneven spacing from the source to the slab interface is negligible. Under this approximation, the feasible resolution equals to the double distance between the wire endings at the input interface.[1] To estimate the magnification, however, we can safely assume that the source is located on a spherical surface concentric to the output interface, and then the magnification factor reads

$$\mathrm{MF}=\frac{R}{R-l}, \tag{1}$$

where $R$ is the curvature radius of the output interface and $l$ is the length of wires.

In theory,[3,7] only the normal (with respect to the slab interfaces) component of electric field of a TM-polarized wave can be completely restored at the slab output interface. The other two field components contain the contributions from TE-polarized waves as well, and in this implementation would be reproduced with some distortion. For this reason, below we present only the simulation results for the following electric field components: In the source region, we show the component perpendicular to the source-region plane, and in the canalized field region, we show the radial component of electric field.

Figure 2 depicts the simulated results. We have performed simulations at several frequencies in the vicinity of 900 MHz to identify the frequency that corresponds to the Fabry-Pérot resonance [the electrical thickness of the slab in this frequency range is roughly three wavelengths ($3\lambda$)]. The results indicate that the realized operational frequency corresponds approximately to 910 MHz, and at this frequency, the electrical length of the wires is about $3.03\lambda$. A small deviation from the theoretical Fabry-Pérot condition is most likely caused by the radially enlarging characteristic dimension of the slab. As predicted, at the operational frequency, the source distribution is not affected by reflections, and the details of the distribution are canalized and simultaneously magnified across the slab. The letter *M* (radial electric field component) is accurately reproduced in the canalized field region, and the characteristic size of the pattern is magnified by a factor of 3. Additional simulations (not shown) indicate that when the canalized field distribution is scanned very close to the output interface, the reradiation of the field from the wire endings is clearly visible. However, when the field is scanned at a distance corresponding to the half of the lattice period at the output interface, this interference vanishes.

Simulations performed at frequencies deviating from the predicted Fabry-Pérot resonance indicate the following (see Fig. 2): As the frequency is tuned below the predicted Fabry-Pérot resonance, strong interference is observed upon a very small frequency shift (see Fig. 2). The authors of Ref. 7 speculated that such interference (for a "regular" canalization slab) is mainly caused by a strong excitation of surface waves. Theoretical analysis presented in Ref. 6 leads to the same conclusions. Clearly, the degradation of the canalization effect is not so rapid when the frequency is increased over the Fabry-Pérot resonance. Theoretical analysis dealing with regular canalization structures[6] predicts in this case that the obtainable resolution slightly decreases with increasing frequency. However, experimental results presented in Ref. 7 indicate that such a degradation is barely visible. Indeed, the meander-line source distribution considered in the paper of Ref. 7 is strongly affected by reflections from the slab input interface, but nevertheless, the modified (distorted) source distribution is still well canalized at frequencies above the Fabry-Pérot resonance.

In the simulation scenario considered here, reflections from the input interface affect the details of the source distribution only very moderately in the frequency range of 910–930 MHz. However, in the canalized field region, clear interference caused by the slab edges is observed as the frequency deviates from the Fabry-Pérot resonance. Additional simulations (not shown) performed in the frequency range of 930–1000 MHz indicate that the source field disturbance caused by reflections (with this particular source) is rather moderate over the entire frequency range. The form of the canalized letter *M* can be somehow recognized up to 960 MHz, but at higher frequencies the image is strongly disturbed. It is important to note that the geometrical details and the feeding technique of the source rather strongly dictate how noticeable is the degradation of the initial source distribution due to reflections from the input interface. This fact is more extensively discussed in Ref. 7. Obviously, due to a smaller amount of subwavelength details, the letter *M* is more tolerant to reflections as compared, e.g., to the meander line considered in Ref. 7.

In conclusion, in this letter, we have demonstrated simultaneous canalization and magnification of subwavelength field pattern in the microwave regime using a specialized wire medium slab. The proposed structure is an array of metal wires, with the separation between adjacent wires being radially enlarged. With the sample simulations, we have shown that the near field pattern of a complex-shaped current source is canalized over an electrical distance corresponding roughly to $3\lambda$, and at the same time it is magnified by a factor of 3. Simulation results showing the performance of the slab at several frequencies deviating from the operational frequency have been also presented and analyzed.

It is important to note that apart from the magnification effect, the proposed slab can be utilized in the opposite way. Electrically large source distributions can be "concentrated" by placing the source at the opposite slab interface. In this case, the source pattern is also canalized through the slab, but the characteristic dimensions of the pattern are scaled down.


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