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Slow-wave substrate integrated waveguide with rotary tensor unit cells for filters application

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Abstract This paper reports slow-wave substrate integrated waveguide (SW-SIW) with rotary tensor unit cells and its applications to filters design. The proposed cross-shaped tensor unit cell can show anisotropic guided-wave parameters of interest, namely its equivalent permittivity and permeability along the transverse direction are different from those along the longitudinal direction. Hence, as rotating the tensor unit cells, equivalent permittivity and permeability of the SW-SIW will be varied, thus its guided-wave properties can be adjusted flexibly. Moreover, the proposed SW-SIW is utilized to constitute slow-wave cavity for filters design. By rotating the tensor unit cells with various angles, equivalent permeability and permittivity of the cavity can be changed as well, which will further influence the cavity’s resonant frequency differently. Experimental results of the proposed SW-SIW cavity filters are in good agreement with simulations, which indicate that the filters’ resonance and coupling properties can be adjusted by rotating the tensor unit cells.

key words: filters, permeability tensor, slow-wave effect, substrate integrate waveguide (SIW)

Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

Substrate integrated waveguide (SIW) is a great platform to design planar microwave components and circuits [1]-[6]. However, its practical applications are limited by its bulky size, which is mainly determined by the inherent relationship between SIW’s width and cutoff frequency. To reduce the size of SIW and improve its practicability, various methods have been proposed [7]-[16]. As a good alternative for size reduction, capacitive slow-wave SIW (SW-SIW) is patterned with periodic blind-vias, which can effectively enhance the equivalent permittivity, thus decreases the cutoff frequency and squeezes the physical size finally [15]-[16]. In [17] to [20], polyline-patterned SW-SIW was developed. Patterning polyline unit cells can enlarge the equivalent inductance of SW-SIW but exert little influence on equivalent capacitance. Then, the equivalent permeability is enhanced notably while the equivalent permittivity varies only a little, so that slow-wave effect is manifested and size reduction is achieved on the premise of keeping easy fabrication and simple structure, indicating promises for practical applications. In this work, SW-SIW with cross-shaped tensor unit cells is proposed and utilized to design cavity filters. By rotating tensor unit cells with various angles, equivalent permeability and permittivity of the cavity can be varied differently, so that the resonance and coupling properties of proposed SW-SIW cavity filters can be controlled as well. This is quite different from the conventional SIW filters, in which the resonance and coupling properties are mainly controlled by lengths, widths and heights of the cavities. Section 2 gives equivalent circuit analyses of the proposed tensor unit cell and SW-SIW. Section 3 shows extraction of the proposed unit cell’s equivalent parameters, as well as guided-wave properties of the SW-SIW with unit cells rotating at different angles. Experiments of the proposed SW-SIW filters design is shown in Section 4, with a conclusion given finally.

2. SW-SIW with cross-shaped tensor unit cells

Geometry and equivalent circuit model of the proposed cross-shaped tensor unit cell is shown in Fig. 1(a). It consists of two perpendicularly crossing microstrip lines, one is line-shaped and the other is wave-shaped. Due to the two crossing microstrip lines being different from each other, the entire structure can be regarded as tensor unit cell [21]-[25]. $L_x/2$ and $L_y/2$ denote the equivalent inductances contributed from the line-shaped and wave-shaped microstrips in the proposed unit cell, respectively. $C_tr$ is the equivalent grounded capacitance. $R_s, R_t$ and $R_p$ separately denote the equivalent resistance along $z$-, $x$-, and $y$-axis. Then, by periodically patterning the proposed unit cell into the conventional SIW, the SW-SIW is constituted. Figure 1(b) shows diagram of the proposed SW-SIW with tensor unit cells, as well as two microstrip line at the input/output ports for impedance transition. Here, $x$-axis is the transverse standing waves direction and $z$-axis is the traveling wave direction.

Based on the effective medium theory in [22], the proposed electrically-small tensor unit cell in Fig. 1 can
be equivalent as an effective homogeneous medium. Then the SW-SIW with periodic tensor unit cells can be regarded as homogeneous medium as well. Patterning cross-shaped unit cells can effectively enhance the equivalent permittivity of SW-SIW while barely change its equivalent permittivity, thus the product of equivalent permittivity and permeability can be increased notably. In this way, the dominant cutoff frequency of SW-SIW can be decreased and slow-wave effect can be exhibited demonstrably. Moreover, since the tensor unit cell is with different shapes along different directions, its equivalent permeability and permittivity should be synthesized in matrix form as below [25]-[29]:

$$\begin{align*}
\mu_e &= \begin{bmatrix} \mu_{ix} & \mu_{iy} & \mu_{iz} \\ 1 & -\mu_{iy} & \mu_{iz} \\ \mu_{iz} & \mu_{iy} & \mu_{ix} \end{bmatrix} \\
\varepsilon_e &= \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix}
\end{align*}$$ (1)

where $\mu_{ix}$, $\mu_{iy}$ are the effective permeability along x- and y-axis, respectively. $\varepsilon_{xx}$ is the effective permittivity along y-axis. $\varepsilon_r$ is the relative permittivity of the host substrate. $\omega$ is the permittivity in free space.

Subsequently, as depicted in [20] and [25], by applying Analogy principle, the effective permeability along x- and permittivity along y-axis can be expressed as:

$$\begin{align*}
\mu_{ix} &= L_x + R_y / (j\omega) \\
\varepsilon_{xx} &= C_x + G_y / (j\omega) = C_x + 1 / (j\omega R_y)
\end{align*}$$ (3) (4)

Similarly, the permeability along z-axis is:

$$\mu_{iz} = L_z + R_z / (j\omega)$$ (5)

3. Parameter tensors of the unit cell with rotation

As the proposed unit cell rotates, its equivalent material parameters will be quite different, as well as those of the SW-SIW. Hence, it is essential to further investigate the proposed cross-shaped unit cell with rotation and extract its equivalent permittivity and permeability tensors. A simulated model of the proposed cross-shaped unit cell with rotation is shown in Fig. 2, as well as two Cartesian coordinate systems. Firstly, by anticlockwise rotating the unit cell for $\theta$, the $(x, y, z)$ system shifts to the $(q_2, q_3, q_1)$ system. Moreover, as the proposed unit cell is a sub-wavelength structure, its effect to the entire medium can be regarded as a unique influence related to the material parameters of substrate. Therefore, the effective material parameter tensors of the proposed unit cell in the $(q_2, q_3, q_1)$ system can be simplified as [30]:

$$\begin{align*}
\mu_{q-q} &= \begin{bmatrix} \mu_{ix} & \mu_{iy} & \mu_{iz} \\ \mu_{iz} & \mu_{iy} & \mu_{ix} \\ \mu_{iy} & \mu_{ix} & \mu_{iz} \end{bmatrix} \\
\varepsilon_{q-q} &= \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix}
\end{align*}$$ (6) (7)

Here, $\mu_{ix}$, $\mu_{iy}$, $\mu_{iz}$ and $\mu_{iz}$ are coefficients of the effective permeability of the unit cell in the $(q_2, q_3, q_1)$ system. Due to the reciprocity of the proposed unit cell, $\mu_{iz} = \mu_{ix}$.

Secondly, as the unit cell rotates, both the line-shaped and wave-shaped microstrips of the proposed unit cell will simultaneously generate equivalent inductance effect along the x- and z-axis of the $(x, y, z)$ system. That is to say, the original equivalent inductance $L_x$ and $L_z$ will be decomposed along the x- and z-axis of the $(x, y, z)$ system, as well as the original equivalent resistance $R_x$ and $R_z$.

Hence, by considering (1), (2), (6) and Fig. 2 together, coefficients of the effective permeability and permeability tensors in the $(x, y, z)$ system will be:

$$\begin{align*}
\mu_{ix} &= \mu_{ix}(\omega) \cos \theta + \mu_{iy}(\omega) \sin \theta \\
\mu_{iy} &= \mu_{ix}(\omega) \sin \theta + \mu_{iy}(\omega) \cos \theta \\
\mu_{iz} &= \mu_{iz}(\omega) \sin \theta \cos \theta - \mu_{iz}(\omega) \sin \theta \cos \theta \\
\varepsilon_{xx} &= \varepsilon_{xx}(\omega)
\end{align*}$$ (8)

By applying (3), (4), (5) to (8), coefficients of the material parameter in the $(q_2, q_3, q_1)$ system will be:

$$\begin{align*}
\mu_{iq}(\omega) &= \frac{\mu_{ix}(\omega) \sin^2 \theta - \mu_{iy}(\omega) \cos^2 \theta}{\sin^2 \theta - \cos^2 \theta} \\
\mu_{iq}(\omega) &= \frac{\mu_{ix}(\omega) \sin^2 \theta - \mu_{iy}(\omega) \cos^2 \theta}{\sin^2 \theta - \cos^2 \theta}
\end{align*}$$ (9) (10)

Three, to extract the parameter tensors of the proposed unit cell with rotation, the Eigen-mode calculator in ANSYS High Frequency Structure Simulator (HFSS) with a master-slave boundary condition is utilized. In the simulation, the host substrate is set with a thickness of 0.508mm, a relative permittivity of 2.94, and a relative permeability of 1. The unit length is 1.6mm, and width of the line-shaped microstrip is 0.2mm. The wave-shaped microstrip is with a major radius of 0.8mm and a minor radius of 0.4mm. In the extraction of parameter tensors, three different directions are initially selected and phase difference along these selected directions is setup. This procedure can be equivalently realized by delimiting three different pairs of wave number simultaneously.
along the x- and z-direction, namely \( k_x \) and \( k_z \). Later, Eigen-mode resonance frequencies of the proposed unit cell under these three pairs of delimited wave numbers can be calculated. With these Eigen-mode resonance frequencies, the nonlinear equations for \( \mu_{xx} \), \( \mu_{zz} \), and \( \mu_{xz} \) can be solved and consequently to obtain the effective permeability tensor eventually.

\[ \text{Fig. 3} \text{ Simulated relative effective permeability tensor of the proposed unit cell at various frequencies.} \]

Meanwhile, it is well known that practical applications typically have demands on the wideband performance of the proposed unit cell with fixed dimensions. Therefore, the effective permeability tensor of the proposed unit cell without \((\theta=0^\circ)\) and with rotation \((\theta=45^\circ)\) in broadband is further explored, with the simulated results shown in Fig. 3. According to Fig. 3, as \( \theta=0^\circ \), \( \mu_{zz} \), the interrelation between \( \mu_{xx} \) and \( \mu_{zz} \) is nearly zero from 8GHz to 16GHz. This is mainly attributed from the orthogonality between the line-shaped and wave-shaped microstrips. Moreover, as the frequency shifts higher, \( \mu_{zz} \) increases a bit while \( \mu_{xx} \) is nearly unchanged. Meanwhile, \( \mu_{xz} \) is larger than \( \mu_{zz} \) in 8-16GHz, which means the proposed unit cell without rotation can exhibit stronger slow-wave effect along x-axis than that along z-axis. Furthermore, for the case of \( \theta=45^\circ \), it can be captured that \( \mu_{xz} \) and \( \mu_{zz} \) are equal to each other, and their value only changes quite slightly from 1.255\( \mu_0 \) to 1.272\( \mu_0 \) in 8-16GHz. Moreover, with the frequency shifting higher, the relative interrelation \( \mu_{xz}/\mu_0 \) also decreases from 0.220 to 0.235. Therefore, as the proposed unit cell rotates from \( 0^\circ \) to \( 45^\circ \), \( \mu_{zz} \) decreases but \( \mu_{xz} \) increases, until they meet with each other, and \( \mu_{zz} \) will shift away from zero. Hence, by considering Fig. 3 with (8)-(11), it can be predicted, as the unit cell rotates from \( 45^\circ \) to \( 90^\circ \), \( \mu_{zz} \) will keep decreasing while \( \mu_{xz} \) keeps increasing, and \( \mu_{xz} \) will move back to zero. In fact, with the unit cell rotating, \( \mu_{xz} \) of \( \theta=90^\circ \) will be the very \( \mu_{xx} \) of \( \theta=0^\circ \), while \( \mu_{zz} \) of \( \theta=0^\circ \) will be the very \( \mu_{cz} \) of \( \theta=90^\circ \). \( \mu_{xz} \) of \( \theta=0^\circ \) and \( \mu_{zx} \) of \( \theta=90^\circ \) are identical, which are far different from other cases including \( \theta=45^\circ \). Additionally, it can be further obtained that the equivalent permeability tensor of the proposed unit cell is somehow insensitive to frequency. Thereby, values of the equivalent permeability tensor can be treated as constants in the frequency range of interest. Coefficients of the equivalent permeability in

\[ \text{Fig. 4} \text{ Calculated and simulated phase constants of the proposed SW-SIW with various angles of rotation.} \]

Afterwards, to verify the aforementioned analyses, some full-wave electromagnetic simulations are carried out. In these simulations, the substrate is set with a thickness of 0.2 mm, a relative permittivity of 2.94, a dielectric loss tangent of 0.0012, a relative permeability of 1.0, and a magnetic loss tangent of 0. The surface conductor is with a thickness of 0.035 mm. Here, the substrate is set as a nonmagnetic material, which will be quite useful to evaluate the permeability contribution from the proposed cross-shaped unit cell. Figure 4 shows calculated and simulated phase constant of the proposed SW-SIW with various angles of rotation. Obviously, as the patterned unit cells rotate from \( 0^\circ \) to \( 90^\circ \), the cutoff frequency can be decreased from 9.15 GHz to 8.4 GHz. Hence, with the tensor unit cells rotating, the slow wave effect can be adjusted and the cutoff frequency will be controlled flexibly. Moreover, the size miniaturization can also be enhanced by rotating the patterned tensor unit cells.

4. Application to cavity filters design

Based on the aforementioned analyses and simulations, as the patterned cross-shaped tensor unit cells rotate, the
SW-SIW will exhibit different guided-wave properties. Therefore, to demonstrate the potential applications of this characteristic, the proposed SW-SIW with rotary cross-shaped tensor unit cells is utilized to form SW-SIW cavities and design filters.

Figure 5(a) gives geometry of the proposed SW-SIW cavity with cross-shaped tensor unit cells. By rotating the tensor unit cells of different angles \( \theta \), different cavities are formed. By considering the aforementioned analyses of SW-SIW with Fig. 5, it can be predicted that the proposed SW-SIW cavity is quite different from its conventional SIW counterparts. Firstly, with the tensor unit cells patterning, equivalent permeability of the proposed SW-SIW cavity will be enhanced effectively while its equivalent permittivity varies only a little. This will generate slow-wave effect and bring in notable size reduction to the cavities. Secondly, as tensor unit cells rotate, the equivalent permeability and permittivity of SW-SIW will change differently. For SIW and SW-SIW cavities, the fundamental resonant mode is TE101 mode, with the resonant frequency can be calculated as:

\[
\begin{align*}
\frac{1}{f_{\text{res}}} &= 2\sqrt{\frac{\mu_0\varepsilon_0\varepsilon_r}{\mu_r\varepsilon_r} \left( \frac{1}{2} \right) + \left( \frac{a}{w} \right)^2} = \frac{1}{2\sqrt{\mu_0\varepsilon_0\varepsilon_r} \left( \frac{1}{2} \right) + \left( \frac{a}{w} \right)^2}
\end{align*}
\]

where \( l \) and \( w \) separately denote length and width of the cavity. \( \mu_0 \) and \( \varepsilon_0 \) are the equivalent permeability and permittivity in the cavity, which can be captured by using (1)-(2) and (8)-(10).

As SIW derives to SW-SIW, cavity’s length \( l \) and width \( w \) keep unchanged. Then, owing to the tensor unit cells patterning, \( \mu_0 \) and \( \varepsilon_0 \) will change differently, leading to the resonant frequency of TE101 mode changes as well. Moreover, as the tensor unit cells rotate, \( \mu_0 \) and \( \varepsilon_0 \) will change accordingly based on its anisotropy, which will bring in extra variation to the resonant frequency. Hence, resonant frequencies of the proposed SW-SIW cavities can be controlled flexibly by rotating the patterned tensor unit cells only, without varying the sizes of cavities. This method brings in another control means, much different from the conventional ones, to design SIW cavity filters. Figure 5(b) to 5(e) shows electrical field distributions of fundamental Eigenmodes in conventional SIW and SW-SIW cavities with various \( \theta \). Here the same substrate setup as that in Section 3 is used. As shown in Fig. 5, by patterning the tensor unit cells, resonant frequency of the fundamental Eigenmode shifts from 7.395GHz for SIW cavity to near 6GHz for SW-SIW cavities. As tensor unit cells rotate from 0° to 90°, the resonant frequency moves higher to 6.373GHz firstly and then lower to 5.929GHz. For a resonant frequency of 5.945GHz, the conventional SIW cavity is with a size of 20.6mm\( \times \)20.6mm, while the proposed SW-SIW cavity (\( \theta=0° \)) occupies 16mm\( \times \)16mm, showing a size reduction of 39.6%. Therefore, patterning tensor unit cells can decrease the resonant frequency of cavity and reduce its size; and rotating tensor unit cells can further control the resonant frequency and achieve various size reduction.

Thereafter, the proposed SW-SIW cavities with various \( \theta \) are utilized to design filters. For the simplification of synthesis, design and rapid prototyping, all the filters are two-pole, as shown in Fig. 6. The initial SW-SIW filter is designed with a central frequency of 8.5GHz, a fractional bandwidth (FBW) of 2.6%, and an in-band insertion loss ripple of 0.1dB. Hence, the initiated inner coupling coefficients \( (k_i) \) and external quality factor \( (Q_e) \) of the proposed SW-SIW cavity filters are calculated by using elements of the Chebyshev lowpass prototype filter. For this case, the coupling coefficient \( k_{12} \) and the external quality factor \( Q_e \) are initially calculated as: \( k_{12} = 0.0359 \), \( Q_e = 32.423 \). Then, \( k_i \) and \( Q_e \) of the proposed SW-SIW cavity filters are numerically studied. Figure 7(a) shows relation between \( k_i \), \( \theta \), and the size of coupling window \( p_1 \). The scaled simulation model is given in the inset as
well. As \( p1 \) becomes larger, i.e., the coupling window gets wider, \( k_0 \) increases. As \( \theta \) rotates larger, \( k_0 \) will be weakened a bit. Moreover, Fig. 7(b) gives the simulated results of \( Q_e \), which is mainly determined by the feeding depth \( d1 \), the feeding window width \( p2 \), and \( \theta \). It can be easily captured that as the \( p2 \) becomes wider, \( Q_e \) will decrease gradually. Meanwhile, a bigger feeding depth or a larger rotation angle can contribute to a higher \( Q_e \).

Later, by taking Fig. 7 and the calculated \( k_{12} \) and \( Q_e \) into consideration, the initiated geometrical parameters of the proposed SW-SIW cavity filters can be initially selected. Finally, all the three cavity filters with various \( \theta \) are simulated and optimized by using a full-wave simulator and the artificial tuning strategy. Firstly, initial values of geometrical parameters obtained from Eigenmode and coupling analyses are set as median values. Then, two values, one is larger and the other is smaller than the median one, are chosen for each geometrical parameter. Thirdly, SW-SIW cavity filters with large, median and small geometrical dimensions are simulated one by one. Then, by comparing these simulations, the interrelation between geometrical values and transmission properties can be easily summarized, which can make the capture of the optimized geometrical parameters be much faster. Moreover, in the proposed design, some key geometrical parameters of the filters, including sizes of the cavities, sizes of the tensor unit cells, and widths of the coupling and feeding windows, are supposed to be simulated and tuned firstly. In this way, the numerical optimizations of the proposed SW-SIW cavity filters can be more efficient. After sufficient simulations, the optimized geometrical parameters are given in Fig. 6 as well, with \( \theta \) of the three filters being set as \( 0^\circ \), \( 45^\circ \), and \( 90^\circ \), respectively. By using the printed circuit board process, prototypes of the proposed SW-SIW cavity filters with cross-shaped tensor unit cells of \( 0^\circ \), \( 45^\circ \), and \( 90^\circ \)-rotation are fabricated on a Rogers RT/Duriod 6002 substrate, with a thickness of 0.508mm, a relative permittivity of 2.2±0.02, and a loss tangent of 0.0023. Photographs of the three fabricated SW-SIW cavity filters are given in the insets of Fig. 8(a), 8(b), and 8(c), respectively. It can be easily captured that the functional parts of the fabricated SW-SIW cavity filters have an identical size of 15mm×26mm.

The fabricated SW-SIW cavity filters are measured by using a Keysight N5230A vector network analyzer. Figure 8 shows measured and simulated results of the fabricated SW-SIW cavity filters with tensor unit cells of various \( \theta \). According to Fig. 8(a), the fabricated SW-SIW cavity filter with tensor unit cells of \( 0^\circ \)-rotation achieves a central frequency of 8.2GHz and a bandwidth of 280MHz, corresponding to a FBW of 3.3%. Its in-band insertion loss is 2.37dB, and the in-band return loss is better than 13.5dB. For the fabricated SW-SIW cavity filter with tensor unit cells of \( 45^\circ \)-rotation in Fig. 8(b), its center frequency is 8.55GHz, with a FBW of 3.5%, an insertion loss of 2.31dB, and a return loss over 20dB. Moreover, as shown in Fig. 8(c), the fabricated SW-SIW cavity filter with tensor unit cells of \( 90^\circ \)-rotation exhibits a center frequency about 8.4GHz, a FBW of 2.86%, an insertion loss of 2.50dB, and a return loss of 15dB.

![Fig. 8 Experimental results of the fabricated SW-SIW filters with tensor unit cells of various \( \theta \). (a) \( \theta = 0^\circ \), (b) \( \theta = 45^\circ \), and (c) \( \theta = 90^\circ \).](image)

 Afterwards, it is worth mentioning that, for all the three fabricated SW-SIW cavity filters, their measurements agree with their corresponding simulations quite well. However, two differences can still be captured: The measured insertion losses of all the three fabricated cavity filters are a bit larger than the simulated ones; The measured bandwidths are narrower than the simulations as well. These two small differences are mainly resulted from the fabrication inaccuracy and the soldering of SMA connectors. Actually, according to the datasheet released by Angels Electronics Co., the commercial SMA connectors can bring in 0.35dB extra loss around 8GHz. Hence, by taking this extra loss into consideration, the simulated and measured insertion losses of all the fabricated SW-SIW filters are in quite good agreement. Finally, it can be summarized from Fig. 8 that, as the tensor unit cells rotate from \( 0^\circ \) to \( 90^\circ \), the resonant
frequency shifts higher firstly and then moves lower, instead of monotonously downwards or upwards. Meanwhile, with $\theta$ shifting from 0° to 90°, the bandwidth becomes larger firstly and then gets smaller again, instead of changing monotonously. Therefore, this unique phenomenon indicates that operation frequencies and bandwidths of the proposed SW-SIW cavity filters can be controlled flexibly by rotating the cross-shaped tensor unit cells.

5. Conclusion

This work studied SW-SIW with the proposed cross-shaped tensor unit cells. Influence from rotating the tensor unit cells on the material parameters and the phase constant of SW-SIW has been investigated theoretically and numerically in detail. Moreover, the proposed SW-SIW with cross-shaped tensor unit cells of various $\theta$ has been utilized to form SW-SIW cavity and design filters. In the proposed SW-SIW cavity filters, patterning tensor unit cells is used to generate slow-wave effect and realize size reduction. Rotating the tensor unit cells is utilized to adjust the equivalent permeability and permittivity of the SW-SIW, and eventually control the resonant frequency and coupling properties. Thus, this is quite different from the conventional SIW cavity to control the resonance by adjusting cavity’s size, and brings in an extra freedom for the SIW filter design. Three SW-SIW cavity filters with various rotary tensor unit cells have been realized, with their simulations agree well with the corresponding measurements. Experimental results of the proposed SW-SIW cavity filters have shown that by rotating the cross-shaped tensor unit cells, both operation frequencies and bandwidths of the SW-SIW cavity filters can be controlled flexibly, which indicates promising potential for compact microwave components applications.

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