Distributed Periodic Structures: Bragg Diffraction and Long-Wavelength Left-Handed Refraction

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Our group has been developing a **transmission line approach of metamaterials,** which include left-handed (LH), right-handed (RH) and composite left-right-handed (CRLH) structures (C. Caloz, H. Okabe, T. Iwai, and T. Itoh, "Transmission Line Approach of Left-Handed (LH) Materials", USNC/URSI National Radio Science Meeting, vol. 1, p. 39, San Antonio, TX, June 2002) and demonstrating **novel microwave applications** (including tight/broadband couplers, backfire-to-endfire leaky-wave antennas, phase-conjugation negative meta-interfaces) based on this approach (C. Caloz, and T. Itoh, "Novel Microwave Devices and Structures Based on the Transmission Line Approach of Meta-Materials", *to be published in IEEE-MTT Int'l Symp.,* Philadelphia, PA, June 2003).

In general, the **LH structures** investigated by most of the groups so far were **periodic** (one exception is I. Lin, C. Caloz, and T. Itoh, "Transmission Line Approach of Left-Handed (LH) Non-Uniform Transmission Lines (NTL)", Asia-Pacific Microwave Conference, vol. 3, pp. 1501-1504, Kyoto, Japan, November 2002) because of convenience: it is easier to analyze and fabricate a periodic than an aperiodic structure.

Photonic band-gap (PBG) structures operate in the **Bragg regime** (period $a \approx \lambda/2$), where the emergence of photonic band-gap is a consequence of constructive interferences of the waves reflected from the different **diffraction** sites. Since such interference phenomena are a direct consequence of periodicity, periodicity is an essential attribute of PBGs. In contrast, in an **effective-medium** (average distance between "atoms" $\overline{a}/\lambda \to 0$), EM waves are "myopic" to the microscopic texture of the material, which is "seen" as an isotropic/homogeneous medium; periodicity is therefore not necessary and **refraction** effects are possible. However, **practical implementations** of LH structures necessarily exhibit an average period between those of PBGs and effective media ($0 < \overline{a} < \lambda/2$), and the frontier between the Bragg and long-wavelength effects is not so clear: in a **LH mode** (negative ω-β slope), **effectiveness** is obtained at the highest frequencies, which are close to the **Γ-point** ($a/\lambda=0$) of the dispersion diagram; in contrast, the **X-point** ($a=\lambda/2$) intercepted by the mode at lower frequencies is clearly a **Bragg** point; for frequencies, between the Γ and X points, we have a progressive evolution, from effective medium to non-effective Bragg medium. As a rule of thumb, we may consider that the condition $a<\lambda/4$ (1st half of the Γ-X segment) is satisfying for effectiveness in practical applications.

It should also be noted that any **practical LH structure** is de facto of **CRLH** nature; it exhibits LHness at lower frequencies and RH at higher frequencies with infinite guided wavelength at the transition frequency. This is because parasitic series-L/shunt-C necessarily become dominant over the designed series-C/shunt-L at high frequencies and also because the series-C/shunt-L cannot be considered lumped anymore if frequency is too high.

In particular, **distributed 2D periodic LH structures** have different nature depending on whether they are **open or closed:** if they are **open** they **cannot be purely LH,** because they appear as a simple PEC plate open to air when frequency decreases to DC and the mode becomes RH and TM-like at the lowest frequencies; in contrast, a **closed** structure can have **a fundamental pure LH mode.** But even in the open case, LHness can be dominant and **focusing effects** can be observed. Different structures are presented and compared. **Isotropy** is also discussed and shown to be maximal at the highest frequency of the LH band. Focusing is demonstrated as illustration.