Advanced Bragg structures based on coupling of propagating and cutoff modes have been proposed [1] to advance FELs into THz-bands. Increase of the oversize factor that is necessary for operation in this band leads to (1) dramatic reduction of selectivity of traditional Bragg structures (which are based on coupling of two counter-propagating waves having high group velocities) [2] due to overlapping of the Bragg resonance zones for different waveguide modes and (2) significant drop of absolute values of the reflection coefficient. Similar to gyrotrons the impact of the cutoff mode into the feedback loop results in mode spectrum purification because the distance between the cutoff-waveguide modes is much higher than between the parasitewaves.

Advanced Bragg reflector (ABR) of the planar geometry (fig. 1) is formed from two metal plates having distance between them and corrugated as

\[ a = a_0 + \frac{1}{2} \cos(k_0 z), \]

where \( k_0 = \frac{2\pi}{\lambda_0} \) is the period and \( a_0 \) is the depth of corrugation.

\[ a \approx a_0 + \frac{1}{2} \cos(k_0 z), \]

where \( k_0 = \frac{2\pi}{\lambda_0} \) is the period and \( a_0 \) is the depth of corrugation.

This structure provides the feedback loop including two counter-propagating TEM waves

\[ E = E_0 \left( e^{-i\omega t} + A e^{i\omega t} \right), \]

and a cutoff TM wave

\[ E = E_{c0} \left( \sin(k_0 z) \right), \]

under the Bragg resonance condition

\[ k = k_0. \]

Thus, the period of the advanced Bragg structure is about twice higher than the period of traditional one that is also beneficial at short-wavelength bands. Advanced Bragg structure provides narrow-band reflection near the cutoff frequency \( \omega_c = n c_0/\alpha_0 \) of the wave \( \beta \). Thus, geometrical parameters of the system should satisfy the relation

\[ \alpha_0 = n \alpha_0/2. \]

The first “cold” tests of the advanced Bragg structures were carried out in the millimeter band near 75 GHz using the BWO scalar network analyzer (SNA). The advanced Bragg reflector for these tests was composed of two parallel copper plates with the antisymmetrical rectangular 1D corrugation.

The structure parameters were as following:

\[ l = 100 \, \text{mm}, \quad \ell = 60 \, \text{mm}, \quad d = 4 \, \text{mm}, \quad a_0 = 0.1 \, \text{mm}. \]

According to (2.3-4) such structure should provide resonance coupling of the propagating TEM waves and the quasi-cutoff wave of TM-type at the gap \( a_{0c} = 10 \, \text{mm} \). During the tests the gap was slightly varied near this value. The accuracy of the \( a_{0c} \) adjustment was ±0.05 mm. To excite the structure an adiabatic horn with the extension from the waveguide transverse section of 3.6 1.8 mm (SNA output size) to 100 10.1 mm was used. This horn forms the quasi-TEM wave from the TE_{\nu} wave of standard rectangular waveguide with the power efficiency of 90%.

For comparison the properties of traditional Bragg reflector (TBR) of the same size \( l = 100 \, \text{mm}, \quad \ell = 60 \, \text{mm} \) and with the corrugation depth \( a_0 = 0.15 \, \text{mm} \) were studied. Period of the traditional reflector corrugation was 2 mm to provide coupling of forward and backward TEM waves at 75 GHz.

Simulations of the advanced Bragg reflector (fig. 2a) were carried out using 3D code HFS/SS and compared with the results of “cold” tests for different values of \( a_0 \), (fig. 2b). One can see the results of measurements coincide well with numerical simulations. The reflection band of the advanced Bragg structure is much sharper than of the traditional one. Absolute value of the reflection provided by advanced Bragg structure is also higher.

As discussed above, the resonance frequency strongly depends on the gap between plates. The shift of the reflection zone with variation of \( a_{0c} \) is shown in fig. 2a. Small differences between “cold” tests and simulations can be explained by the uncertainty of the measurements (±0.15%) conditioned by precision of positions of the plates forming the structure as well as by admixture of high-order modes in the forward and backward fluxes.

Measurements and simulations of another ABR were carried out in the band near 60 GHz. This structure was composed of symmetrically corrugated plates with the following parameters:

\[ l = 100 \, \text{mm}, \quad \ell = 75 \, \text{mm}, \quad d = 5 \, \text{mm}, \quad a_0 = 0.05 \, \text{mm}. \]

In this case the propagating TEM waves should be coupled with quasi-cutoff TM_{\nu} wave at the gap \( a_{0c} = 10 \, \text{mm} \). The results are presented in fig. 3. One can see the usage of shallow corrugation at the relatively low oversize parameter \( a_{0c} < 2 \) leads to the extremely sharp resonance reflectivity \((\alpha_0 > 0.1 \%)\).

Conclusion

Advanced Bragg reflectors were simulated and designed for FELs operating in the millimeter and submillimeter bands. Results of “cold” tests at 75 and 60 GHz demonstrated good agreement with the simulations. Narrow-band reflection in the vicinity of the cutoff frequency of the trapped wave was measured and high selective properties of Bragg structures of such type were proved. Tunability of the reflector was achieved in the frequency band of about 4% when varying distance between plates. Coupled-wave analysis together with 3D simulations demonstrate that advanced Bragg structures are able to provide selectivity up to transverse size ~10–20 wavelengths [3]. Compatibility with transportation of an intense electron beam encourages the use of novel Bragg reflectors in powerful long-pulse FELs up to THz frequencies [4].

References


