Simulating Twistronics in Acoustic Metamaterials

S. Minhal Gardezi,[1] Harris Pirie,[2,1] and Jennifer E. Hoffman[2,1]

[1] *School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, 02138, USA*
[2] *Department of Physics, Harvard University, Cambridge, MA, 02138, USA*

(Dated: August 19, 2020)

Abstract: example outline. See final published version in 2D Materials 8, 031002 (2021)

I. INTRODUCTION

1 (motivate interest in TBG but present difficulty in studying quantum materials directly)
Due to their versatility, van der Waals (vdW) heterostructures are useful systems for exploring emergent physical phenomena. Introducing a twist angle between the two-dimensional (2D) layers in a vdW heterostructure can induce exotic properties, making vdW heterostructures compelling platforms for studying tunable correlated behavior. Recently, for example, twisted bilayer graphene (TBG) has been shown to exhibit unconventional superconductivity at certain magic angles. Unfortunately...

2 (motivate phononic metamaterials as quantum mimics)
Phononic metamaterials have unique acoustic properties depending on their macroscopic, often periodic structure. They are specifically useful systems for mimicking quantum behavior.

3 (outline paper, mention COMSOL)
Phononic metamaterials have already shown promise as mimics for vdW heterostructures; here we further demonstrate their usefulness as quantum mimics by creating twisted vdW metamaterials. Using finite element analysis via COMSOL MULTIPHYSICS, we explore the twist angle and coupling strength between layers in metamaterial bilayer graphene to produce flattening Dirac features matching those of TBG. We demonstrate the existence of magic angles at which our metamaterial produces phononic flat bands.

II. PREPARING TO TWIST

4 (present metmaterial graphene)
We begin by constructing a graphene-like monolayer phononic metamaterial. Graphene's characteristic Dirac cone arises from the C_6 symmetry of its atomic honeycomb lattice. Our metamaterial is therefore a honeycomb lattice of cavities in a solid slab, with each pair of neighboring cavities connected by a channel. Propagating acoustic waves are consequently forced to mimic the nearest-neighbor hopping patterns of electrons through graphene, resulting in an isolated Dirac cone (fig 1). We model our device as air cavities in steel, with (insert size specifications). It is interesting to note, however, that so long as the cavities are of significantly lower density than the surrounding solid, acoustic waves are restricted to connected cavities alone. If we insert additional unconnected cavities, the device remains graphene-like (fig 1).

5 (present metamaterial AA and AB-stacked bilayer graphene)
(Figure 1bc)
We next coupled two layers of our graphene-like device to create a metamaterial heterostructure mimicking bilayer graphene. Following previous phononic metamaterial coupling schemes, we insert a HDPE coupling membrane between steel layers in both the AB and AA stacking configurations. Our AB-stacked metamaterial displays a parabolic "kissing" structure while the AA-stacked structure has double Dirac crossings, both mimicking their bilayer graphene counterparts (fig 1).

III. METAMATERIAL TWISTED BILAYER GRAPHENE

6 (Fermi velocity decreases with twist angle)
Introducing a twist angle between metamaterial graphene layers produces a heterostructure closely mimicking TBG (fig 2).

7 (Discuss flat band)
We can create magic-angle mTBG (fig 2c).

8 (Coupling density is analgous to applied pressure)
Just as applying pressure to TBG changes the coupling between graphene layers, altering the interlayer density in mTBG changes the coupling between metamaterial layers (fig 3).

9 (can achieve flat bands at relatively high angles)
In the metamaterial system, we can easily modify the interlayer density to achieve a flat band at a relatively high commensurate angle (fig 4).

10 (Twisting the metamaterial yields good results, expanding our ability to make metamaterial vdW heterostructures.)

11 (Conclusion and implications)

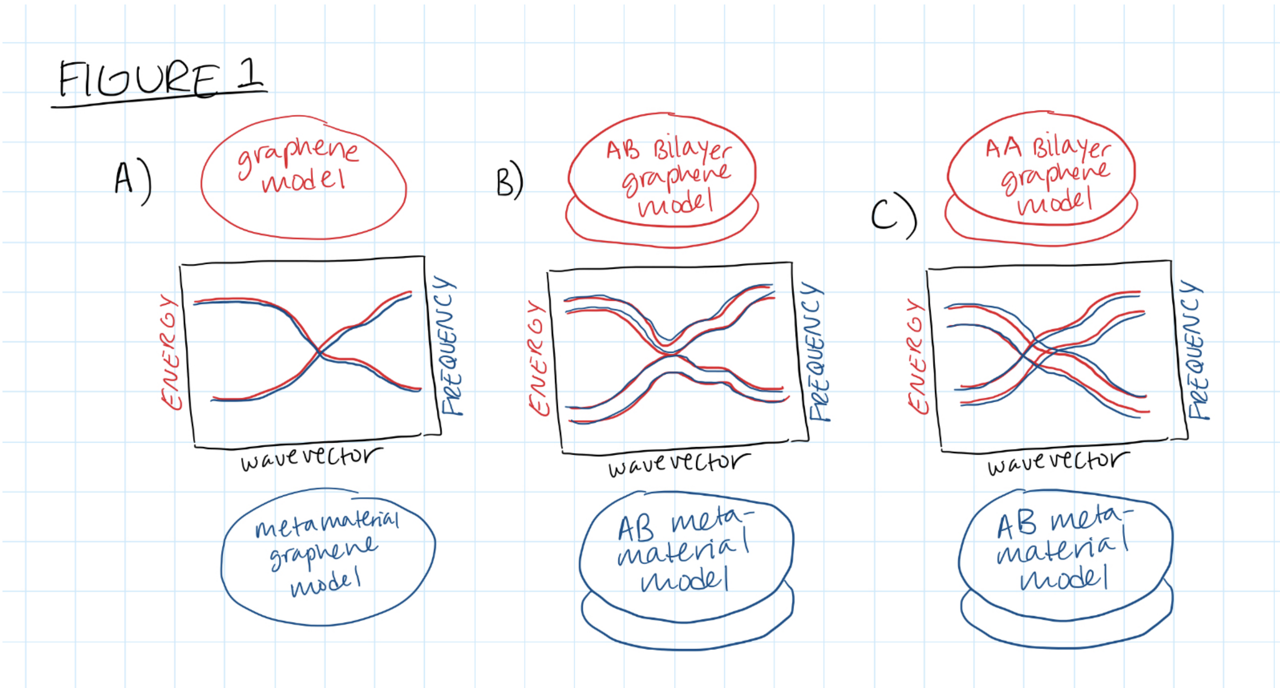

Fig. 1. the metamaterial model for graphene and bilayer graphene is accurate. (Should this be split into two figures? Should I show both versions of metamaterial graphene (with and without holes)?)

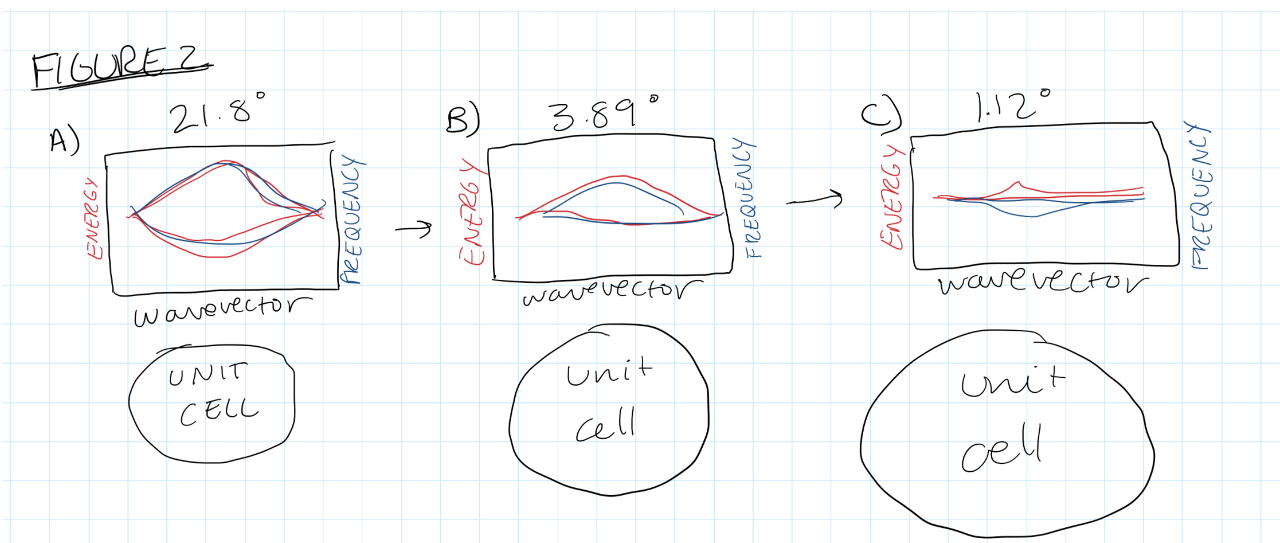

Fig. 2. the metamaterial TBG displays the correct band-flattening trend. the phononic bands closely match the electronic bands, although they are flipped in the vertical direction.

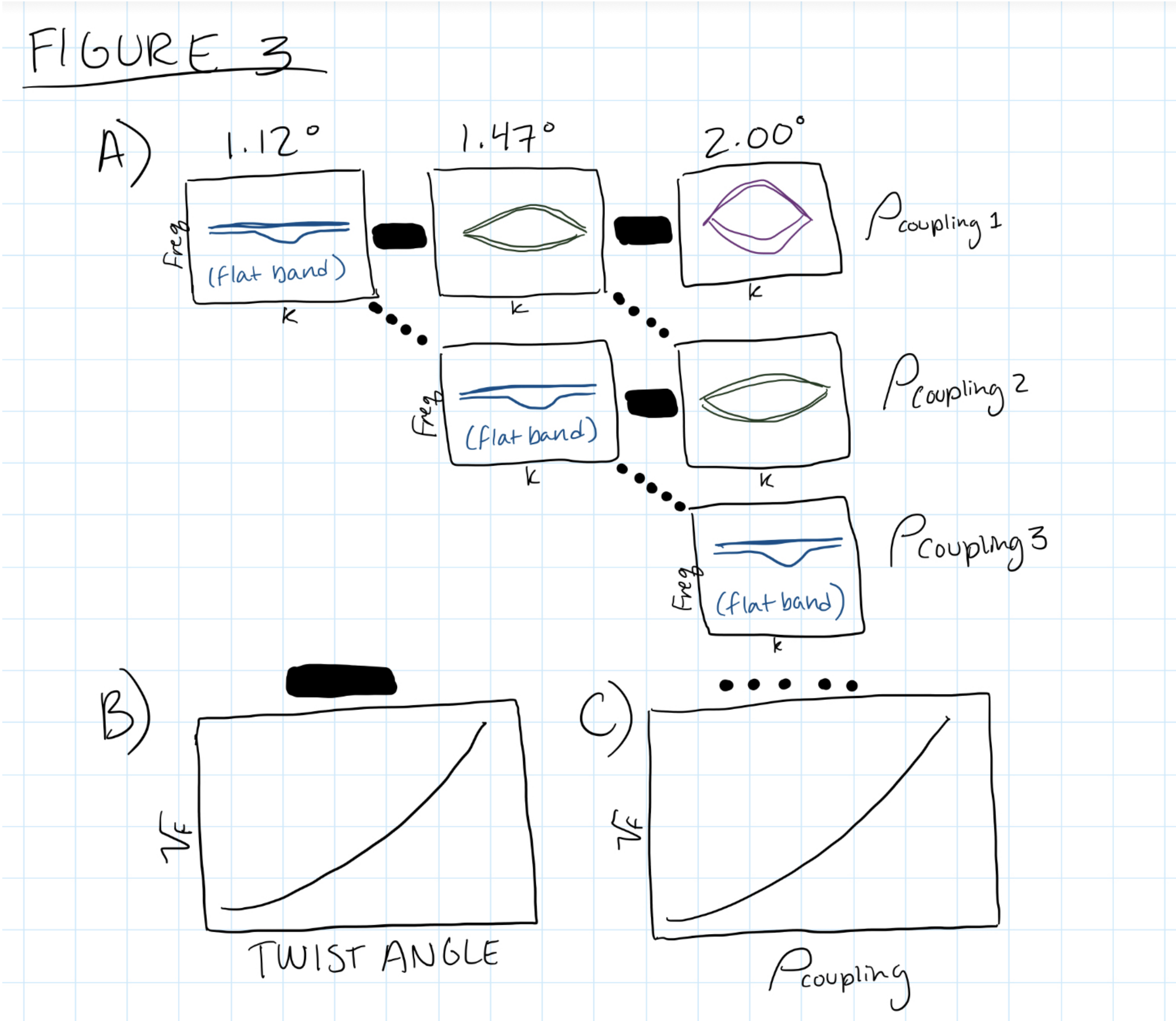

Fig. 3. altering the coupling density alters the angle at which we see certain features. the fermi velocity decreases both as the twist angle decreases and as the coupling density decreases.

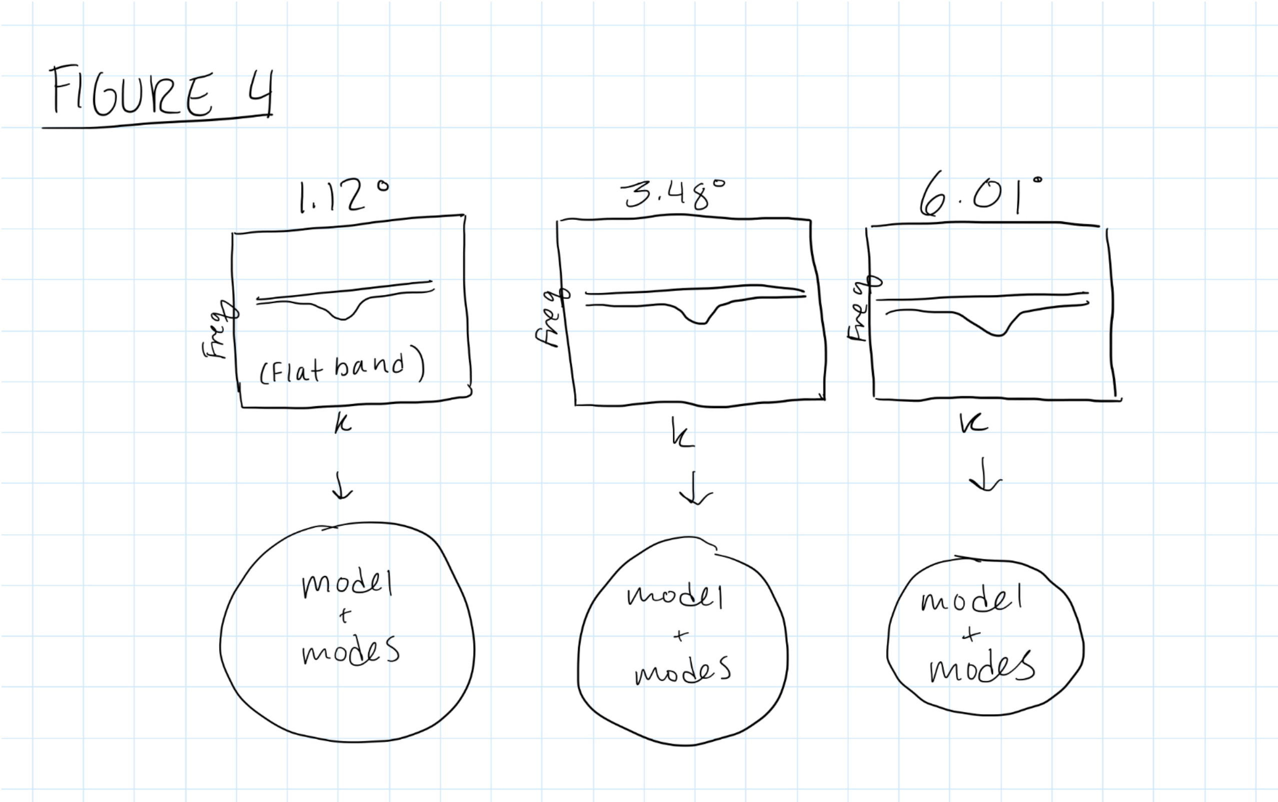

Fig. 4. by altering the coupling density, we can achieve a flat band at relatively high twist angles.